

Research Report

200-1

Custom-Designed Membrane Filtration for Water Treatment Plants

A Technical and Economic Evaluation

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Abstract

This research project evaluated the feasibility of retrofitting a custom designed membrane system as a final separation process in a conventional water treatment plant. This report presents preliminary findings for pilot tests conducted at a water treatment plant (WTP) located in Sheboygan, Wisconsin which treats raw water with conventional unit processes. Settled water was treated, in lieu of granular media filtration, by an ultrafiltration (UF) pilot plant. Two approaches to custom membrane system design are discussed: a gravity-driven process where membranes may be implemented into the existing hydraulic gradeline of a water treatment plant; and a pumped approach that is similar to existing proprietary systems, but offers the benefits of a custom design for maximizing the use of existing infrastructure and lower operating pressures. The custom design UF membrane was successfully demonstrated over the course of 30 days of pilot testing at a flux of 24 gfd with a head of 8.6 psi (20 ft of water). The custom UF membranes were also operated at higher pressures produced with a pump, and successfully operated at a flux of 35 gfd for a period of 30 days at a maximum pressure of 20 psi (46 ft of water). Particle counts in the membrane permeate stream averaged zero counts/ml across all size ranges except the 2–5 μm range where counts averaged only 0.02 counts/ml. Construction cost estimates for the upgrade or retrofit of the 34 mgd Sheboygan WTP predict that the implementation of ozone disinfection to address the inactivation of chlorine-resistant pathogens in the surface water source is less expensive than either of the membrane technologies tested. However, it may be possible to implement the custom membrane system in certain plants at roughly 40 percent of the cost of proprietary UF membrane systems currently available.

Project Overview

Raw water from Lake Michigan and settled water from an existing WTP in Sheboygan, WI, which uses conventional treatment unit processes (*i.e.* coagulation, flocculation, sedimentation, and gravity media filtration) to treat surface water from Lake Michigan, were used as the feed waters for an UF pilot plant to evaluate the feasibility and compare the performance of replacing the existing gravity media filters with a low-head, low-flux membrane system. The pilot membrane system was operated at two different pressures to simulate operation under gravity (*i.e.* existing hydraulic gradeline) and pumped conditions, and at two different flux rates. An interval of 30 days between chemical cleanings was selected and used as an acceptable operational constraint and a design guideline.

Preliminary construction and operations and maintenance (O&M) costs were estimated and compared to costs for the implementation of other advanced treatment technologies including ozone and biologically active filtration (BAF) and high-pressure, high-flux membrane systems.

While not yet recognized by the United States Environmental Protection Agency (EPA) as a disinfection technology equivalent to ozone, preliminary cost estimates for the implementation of an ultraviolet (UV) radiation system are also included.

Water Industry Issues Addressed

Utilities treating surface waters are faced with the challenge of complying with increasingly stringent regulations which require a balance between the removal or inactivation of disease-causing microbes through physical removal and disinfection processes, and limiting the disinfection by-products formed when disinfectants such as chlorine and ozone are used. Of particular concern, are the chlorine resistant pathogens, such as *Cryptosporidium* oocysts, which have caused several well-publicized outbreaks in the Midwest, other locations in the United States, and around the world. To date, utilities seeking to upgrade or improve WTP performance to comply with existing, anticipated, and future regulations have had to choose between disinfection with ozone (and often followed by the use of biologically active filters to remove the biodegradable organic carbon produced) or membrane filtration to ensure robust treatment while limiting the formation of DBPs. Since the occurrence of a Cryptosporidiosis outbreak in Milwaukee, WI in 1993 and other related incidents, some utilities have elected to reduce microbial risks to a level lower than those required in current and anticipated regulations. Concerns about the effective treatment of chlorine resistant pathogens with conventional treatment processes (especially at low water temperatures) have intensified interest in membrane filtration, which presents a virtually absolute barrier to micron-sized particles.

Implementing advanced treatment technologies like ozone with BAF or pressure-driven membranes systems into existing WTPs can be expensive and may not use existing facilities to their fullest extent. Depending upon site specific constraints, it may be necessary to construct:

- Intermediate pumping stations to achieve the hydraulic head necessary for the use of ozone

- New, deeper filter boxes for the use of granular activated carbon media in BAF
- Separate facilities to house the pumps, piping, membranes and other equipment that comprise a proprietary, pressure-driven membrane system

Utilities with treatment capacities greater than 30 mgd generally have not considered the use of pressure-driven membranes due to the high installed cost of the modular, proprietary system designs currently available. The existing systems are limited in capacity to a maximum of about 2 mgd per packaged skid, and so may require many parallel trains of membrane skids to meet capacity needs. Finally, many utilities have significant investments in their existing facilities and are seeking some method to protect and/or recoup these monies especially in WTPs with facilities that have useful service lives exceeding 20 to 30 years.

Custom designed membrane systems using low-head and low-flux membranes may hold promise to reduce installation costs by using existing piping, valves, backwash systems, control systems, and concrete structures (e.g. filter boxes), and buildings. Custom membrane system design would involve the design of membrane related equipment by engineers rather than membrane suppliers. Membrane suppliers would provide only the membranes and membrane modules, with membrane characteristics (e.g. polymers, pore size, and permeability) engineered to fit a given application. Depending upon site-specific constraints, the membranes could be implemented into the existing hydraulic gradeline of a water treatment facility and operate by gravity.

Testing Equipment and Performance Criteria

The project was performed using a custom UF membrane pilot unit, designed by Carollo Engineers, located at the Sheboygan WTP in Sheboygan, WI. The membrane module was procured from Polymem. The WTP uses Lake Michigan as its source, and feed water to the pilot plant included settled water (*i.e.* pretreated with alum in coagulation, flocculation, and sedimentation processes) and raw, untreated water.

The pilot plant is fully automated and allows for remote monitoring and data acquisition. It calculates key operating parameters including: transmembrane pressure, flux, and specific flux.

Operational and water quality criteria used to compare and judge system performance included:

- Operation at fluxes of 24 gallons per square foot per day (gfd) at hydraulic heads of 20 feet of water or less to simulate gravity operation possible at some existing WTPs
- Water recovery of ≥ 90 percent
- Chemical cleaning interval of ≥ 30 days
- Finished water turbidity ≤ 0.1 NTU
- Heterotrophic bacteria counts of zero
- Particle counts of < 1 count per milliliter at sizes $> 2 \mu\text{m}$.

Testing Results

Operation under gravity conditions (*i.e.* heads of 20 feet of water or less) met all performance criteria when operated with settled water at recovery equal to 90 percent. However, the system failed to meet the criterion of greater than a 30 day interval between chemical cleanings when recovery was increased to 95 percent with the same feed water source. The system also met criteria for chemical cleaning frequency and water quality performance when operated with settled water at a flux of 35 gfd and a recovery of 90 percent when the system pressure was increased with the use of a pump to a maximum head of 46 feet of water (*i.e.* about 20 pounds per square inch (psi)). Operation under assumed gravity conditions with raw water at a recovery of 90 percent produced a water quality identical to that produced with settled water, but failed to meet the criterion of greater than a 30 day interval between chemical cleanings. Under these conditions, a chemical cleaning would be required every 16 days at design capacity.

Construction cost estimates for the upgrade or retrofit of the 34 mgd Sheboygan WTP predict that the implementation of ozone disinfection to address the inactivation of chlorine-resistant pathogens in the surface water source is less expensive than either of the membrane technologies tested. The use of ozone may not be feasible at some WTPs because of water quality concerns (*e.g.* disinfection by-products), incompatibility with existing facilities or process constraints (*e.g.* existing hydraulic gradelines), and high operating costs which may be required to meet the inactivation conditions still being developed by the federal government. It may be possible to implement the custom membrane system in certain plants at roughly 40 percent of the cost required for proprietary UF membrane systems currently available. These results may hold promise for the implementation of UF membranes at surface WTPs that heretofore have not considered membranes due to the high cost of the proprietary, modular-based membrane systems.

Recommendations

Additional studies are recommended to confirm project results:

- At other locations with other water sources
- With microbial challenge tests
- With different membrane characteristics (*e.g.* higher permeability)
- With other modifications to the pilot plant unit to optimize chemical cleaning methods and to explore the effect of other pretreatment processes and chemicals (*e.g.* ferric coagulants, lime, and PAC) on membrane performance.

Purpose of the Project

The purpose of the project is to evaluate the feasibility of retrofitting a custom designed membrane system as a final separation process in a conventional water treatment plant.

The challenge of removing and/or inactivating chlorine-resistant pathogens while controlling DBP formation is the main regulatory objective faced by utilities with WTPs treating surface waters. When assessing the need for upgrades to existing water treatment processes, required for meeting current and anticipated regulations, utilities generally have considered ozone with BAF or proprietary, modular MF or UF membrane systems. While these membrane technologies have been demonstrated to outperform ozone with BAF in terms of particulate removal and inactivation efficiency (especially under cold water conditions), the use of membrane processes to treat drinking water has not been considered feasible by utilities with treatment capacities on the order of 30 mgd and greater due to the high construction and operating costs of the modular, proprietary system designs currently available; and an interest in maximizing the return on the investment in existing water treatment facility components.

The project evaluated the performance of the custom membrane system at meeting the following objectives:

- Provision of a physical barrier to microbial pathogens without the formation of DBPs
- Operation using a pressure (*i.e.* 20 ft of water) which may be available within the existing hydraulic gradelines of some WTPs
- Implementation of a membrane process for WTPs with capacities greater than 30 mgd at a reduced capital cost
- Reduced energy costs when compared to other advanced treatment methods

Background Material on Previous Related Research

As opposed to chemical disinfection (*i.e.* chlorine, ozone, etc.), which allows for some degree of inefficiency by short-circuiting, membranes physically prevent pathogens from entering the finished water supply, and, in theory, may be considered an absolute barrier to pathogens. (Crozes, Hagstrom, et al, 1999). In practice, UF systems have been granted up to 4-logs of disinfection credit for removal of pathogens such as *Giardia* cysts. However, operating experience also has shown that membranes may be subject to failure by way of fiber breakage (Jacangelo, Adham, and Lainé, 1997).

While ozonation and pressurized, pump driven membrane filtration have been evaluated previously on Lake Michigan, the work presented in this paper is the first attempt to evaluate membrane filtration operating at pressures similar to those which may be available by gravity at some WTPs and to propose a custom membrane system design concept which may allow the retrofit of existing granular media filters with a membrane (Crozes and Cleveland, 1997), (Crozes, Hagstrom, et al, 1997, 1998), (Cushing, Crozes, and Antencio, 1999).

Membrane Technology Overview

As previously mentioned, proposed and anticipated drinking water regulations that include increasingly stringent standards for pathogen removal and maximum contaminant levels (MCLs) for disinfection by-products provide an impetus for the use of membrane technologies in the United States. With regard to low pressure membrane technologies, both ultrafiltration (UF) and microfiltration (MF) are effective at removing particulate material from water, including pathogens such as *Giardia* cysts, *Cryptosporidium* oocysts, bacteria, and, in the case of UF, viruses (Wright, 1998), (Trussell, et al, 1998). By producing a finished water turbidity consistently lower than 0.1 NTU and by presenting a virtually absolute barrier to the pathogens of concern, UF and MF processes can reliably meet the current Surface Water Treatment Rule (SWTR) filtration and disinfection requirements, as well as standards contained in the Interim Enhanced Surface Water Treatment Rule (IESWTR) and other future regulations.

MF and UF systems present a series of other operational advantages including possible reductions in: chemical use, labor costs, and space requirements; and the potential for remote operation. Recent cost analyses have shown that low pressure membrane filtration appears to be a cost effective option especially for systems with capacities less than 30 mgd. As a result, several membrane filtration plants have been installed and successfully operated for more than nine years for the treatment of raw water supplies with occasional turbidity spikes up to 200 NTU.

Membrane filtration performance, in terms of flux, backwash frequency and chemical cleaning frequency, is highly dependent upon the raw water quality. Flux reduction due to the accumulation of material on or in the membrane skin, is generally referred to in the literature as membrane fouling. For membranes with a hollow fiber or tubular configuration, fouling is partially reversible by applying a pressurized counter flow, commonly called backwash, which removes the majority of the accumulated matter. Membrane manufacturers have developed backwash procedures, specific to the membrane type and configuration, that use permeate water or air. The frequency and duration of the backwashes are adjusted as a function of the raw water quality; both parameters typically are increased when the raw water contaminant load increases.

Over longer periods of operation (e.g. on the order of several weeks or a month) as the number of filtration cycles increases, the degree of membrane fouling not totally reversible by the hydraulic backwash procedure also increases. In order to obtain the desired production flow rates, or flux, an increase in transmembrane pressure is required. When this pressure reaches a maximum allowed by the mechanical resistance of the membrane, chemical cleaning of the membrane is required for the membrane to regain most of its initial permeability. Regardless of the membrane system used, chemical cleaning is typically a cumbersome process and requires the unit being washed to be taken out of service for several hours. Chemical cleaning results in a reduction of the overall plant capacity, and produces a waste that may be difficult to dispose of. There are also concerns that repeated chemical cleaning may affect the membrane service life. Thus, for operational reasons, chemical cleaning should be limited to a frequency on the order of approximately once a month; and irreversible membrane fouling should be carefully evaluated when optimizing the design flux for a given water supply.

None of the classical theories based on the analysis of gel layer formation and accumulation of particulate matter can completely explain the irreversibility of fouling. Research work has shown that the adsorption of low molecular weight molecules, smaller than the membrane pore size, can lead to significant membrane irreversible fouling. Because adsorption phenomena are driven by the nature of the interactions between natural organic matter (NOM) and the membrane, hydrophilic membranes are typically better suited for filtration of surface waters. While it has been clearly demonstrated that the adsorption of humic material into the membrane pores

contributes to the irreversible fouling of selected membranes, operating parameters also impact irreversible fouling (Crozes, Anselme, and Mallevialle, 1993), (Crozes, Jacangelo, and Laine, 1997), and should be evaluated at the pilot scale for a given water supply.

Summary of Key Findings

Operation under gravity conditions assumed (*i.e.* heads of 20 feet or less) met all performance criteria when operated with settled water at recoveries of 90 percent, but failed to meet the criterion of greater than a 30 day interval between chemical cleanings when the recovery was increased to 95 percent with the same feed water source. The system met criteria for chemical cleaning frequency and water quality performance when operated with settled water at a flux of 35 gfd and a recovery of 90 percent when the system head was increased with the use of a pump to a maximum of 46 feet of water (*i.e.* about 20 pounds per square inch (psi)). Operation under assumed gravity conditions with raw water at a recovery of 90 percent produced a water quality identical to that produced with settled water, but failed to meet the criterion of greater than a 30 day interval between chemical cleanings. Under these conditions, a chemical cleaning would be required every 16 days at design capacity.

Construction cost estimates for the upgrade or retrofit of the 34 mgd Sheboygan WTP predict that the implementation of ozone disinfection to address the inactivation of chlorine-resistant pathogens in the surface water source is less expensive than either of the membrane technologies tested. The use of ozone may not be feasible at some WTPs because of water quality concerns (*e.g.* disinfection by-products), incompatibility with existing facilities or process constraints (*e.g.* existing hydraulic gradelines), and high operating costs which may be required to meet the inactivation conditions still being developed by the federal government. It may be possible to implement the custom membrane system at certain plants at roughly 40 percent of the cost of proprietary UF membrane systems currently available. These results may hold promise for the implementation of UF membranes at surface WTPs that heretofore have not considered membranes due to the high cost of the proprietary, modular-based membrane systems.

Testing Site and Duration

Pilot testing was hosted by the Sheboygan Water Utility in Sheboygan, WI. The Sheboygan Water Treatment Plant (WTP) has an estimated treatment capacity of 34 mgd and recorded an average annual day water demand of about 16 mgd in 1999. Sheboygan uses Lake Michigan as its sole source and treats the raw water using alum as the coagulant in a conventional treatment processes (i.e. coagulation, flocculation, sedimentation, and gravity granular media filtration). Source water used for pilot testing included settled water taken after sedimentation and prior to granular media filtration; and untreated Lake Michigan water. Pilot testing commenced at Sheboygan in early February 2000 and was finished in the first week of June 2000.

Custom Membrane Pilot Plant

A flow diagram for the Carollo Engineers' custom UF membrane pilot plant is presented in Figure 1. The pilot plant stores source water in a feed tank from which it is then pumped to the custom UF membrane module. Flow rate (i.e. membrane flux) and system pressure (i.e. head) through the membrane module are monitored and controlled using a programmable logic control (PLC) system which automatically adjusts a variable frequency drive pump and a control valve to maintain a constant head and membrane flux.

Backwash is performed automatically using permeate water that is stored in a 100 gallon storage tank as shown in Figure 1. A backwash pump, also equipped with a variable frequency drive, is used to backwash the membrane at a rate of about 95 gallons per minute (gpm) for a duration of 75 seconds. A chlorine solution, at a concentration of 5 mg/L, is dosed to the membrane pilot during backwash. Air is also used concurrently with the water during the first 60 seconds of backwashing to scour particles from the membrane surface. The intervals between backwashes are set based on system recovery goals (e.g. during the gravity simulation with settled water, a backwash frequency of once per hour corresponded to a recovery of 90 percent).

The membranes are chemically cleaned using a mixture of stored permeate water, caustic soda, and sodium hypochlorite to achieve a pH of 12 and a chlorine residual of 200 mg/L. Chemical cleaning frequency is determined by system operation with the objective of an interval between cleanings exceeding 30 days. Chemical cleaning methods used during the study involved soaking the membranes because the pilot unit is not currently equipped for recirculation of cleaning solutions during backwash. Chemical cleaning strategies are still being evaluated and optimized, and it is envisioned that a full-scale chemical cleaning method would involve soaking and/or recirculation with cleaning solutions for a duration of 2 hours or less.

The custom UF membrane pilot plant is fully automated for remote monitoring and data acquisition. A data acquisition and control system (DAC) monitors selected pilot plant operating variables and calculates key parameters including transmembrane pressure, flux, and specific flux. The DAC system has a human-machine interface that allows pilot plant operators to vary operating conditions, initiate backwashes and chemical cleaning sequences, and recall historical data and trends (Cleveland, et al, 1999). These features are also accessible via remote telemetry.

One of the benefits to custom membrane design is that the owner can specify that the membrane manufacturer fabricate system components (e.g. the membrane material, module design, and membrane permeability) to address site specific water quality and facility conditions. The characteristics of the custom membrane system used in the present study are described in detail in Table 1.

Figure 1: Customer membrane pilot plant flow diagram

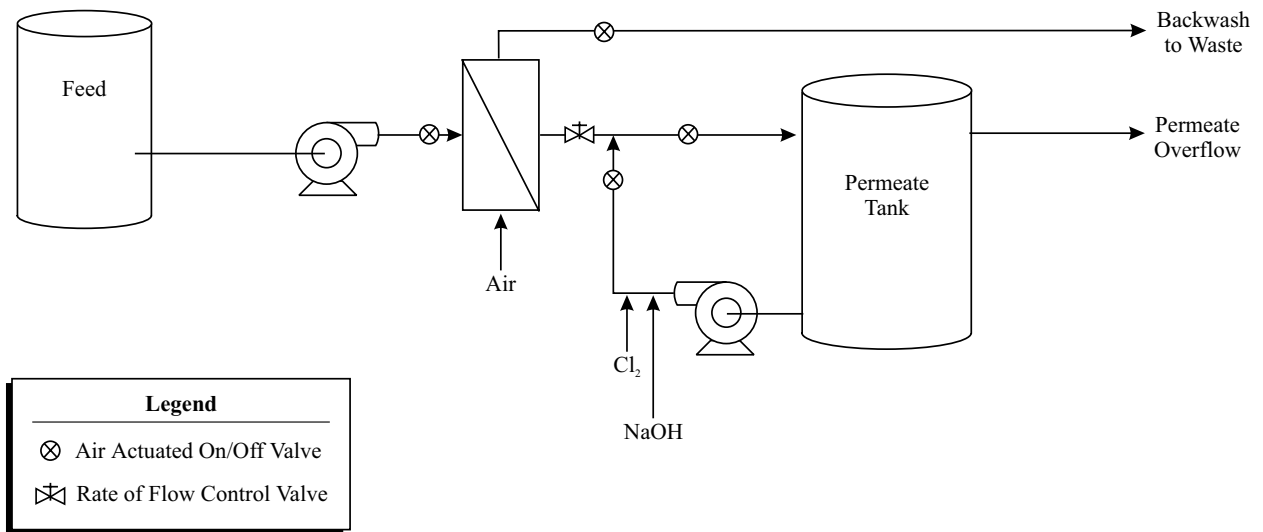


Table 1: Custom membrane system characteristics

	Parameter	Description
Membrane	Material	Polysulfone derivative
	Configuration	Hollow fiber, outside/in U shape bundle, asymmetric, double skin, dense support
	External diameter	0.028 in (0.72 mm)
	Internal diameter	0.015 in (0.38 mm)
	Acceptable free chlorine residual (continuous exposure)	100 mg/L
	Pore size	0.01 μm
	Maximum operating temperature	122°F (50°C)
	Operating pH range	2-13
	Maximum transmembrane pressure (in operation or backwash)	36 psi (2.5 bar)
Module	Dimensions	31.5 in x 12.0 in (0.80 m x 0.30 m)
	Membrane surface area	1270 ft ² (118 m ²)
System	Flow configuration	Dead end at low constant pressure
	Concentrate recirculation	None
	Backwash	Permeate @ 21 to 27 psi (1.4 to 1.8 bar) with chlorine (2 to 5 mg/L residual)
	Backwash flow rate	150 gpm (34 m ³ /h) @ 36 psi (2.5 bar) at 20°C
	Chemical cleaning	Caustic soda, acid, chlorine

Historical Water Quality Data

Selected water quality data of the raw and settled water recorded at the Sheboygan WTP during 1999 are presented in Table 2. The raw water turbidity varied between 0.4 to 72.6 NTU and averaged about 4.7 NTU. Settled water turbidity ranged from a low of 0.2 NTU to a maximum of 2.1 NTU and averaged 0.7 NTU. The temperature of the finished water ranged from 34.0 oF (1.1 oC) to a maximum of 69.0 oF (20.6 oC) and exhibited an average temperature of 46.2oF

(7.9 oC). Raw water pH is depressed slightly following alum coagulation. It is interesting to note that the average settled water pH of 7.0 is below the pKa of most humic substances in water (Snoeyink, 1990). At this pH, some researchers have shown that humic substances are more prone to adsorption on both powdered activated carbon and membranes (Snoeyink, 1990), (Braghetta and Digiano, 1994), (Curry and Zander, 1996).

Table 2: 1999 Annual average water quality data (Sheboygan Water Utility)

	Raw water turbidity		Settled water turbidity		Finished water temperature
	NTU	pH	NTU	pH	°F (°C)
Average	4.7	7.6	0.7	7.0	46.2 (7.9)
Standard deviation	6.7	0.3	0.3	0.2	9.0 (5.0)
Minimum	0.4	6.9	0.2	6.3	34.0 (1.1)
Maximum	72.6	8.7	2.1	8.0	69.0 (20.6)

Water quality along the west shore of Lake Michigan has been studied extensively, and it is considered a high quality water supply source with the following characteristics:

- Moderate hardness of between 120 and 140 mg/L as CaCO₃
- Moderate alkalinity of between 100 to 120 mg/L as CaCO₃
- Moderate to serious algae-related taste and odor episodes in the summer and autumn
- Seasonal algae levels which can pose intermittent treatment problems
- Good microbial quality; however, Lake Michigan is known to contain *Giardia* cysts and *Cryptosporidium* oocysts.

Hydraulic Performance

Custom membranes were pilot tested to simulate the hydraulic conditions associated with two different membrane filtration applications: with an assumed, available head of 20 feet of water (8.7 psi) to simulate gravity head conditions that may be available at some WTPs; and with a higher pressure of 46 feet of water (i.e. about 20 psi) produced by a pump. The hydraulic performance of the custom membrane design evaluated in this study is summarized in Table 3. Condition 1 and Condition 2 represent the results of two, simulated gravity filtration tests (i.e. while the system head and flux were held constant in each case, the recovery was increased to 95 percent in Condition 2) using settled water as a source. Condition 3 was also tested with settled water at a higher flux rate and pressure available with the use of a pump. Condition 4 used raw water as the feed water to the membrane and was operated at hydraulic conditions similar to Condition 1.

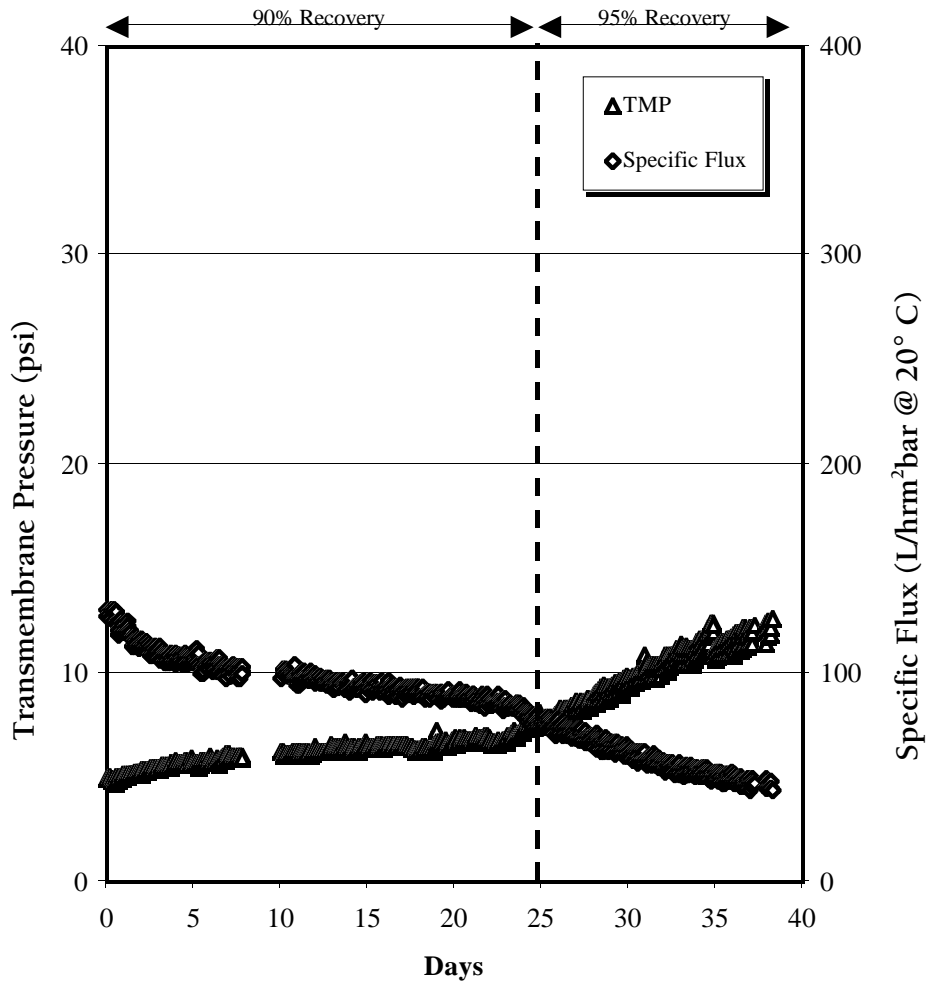
Table 3: Summary of custom membrane pilot test conditions

	Condition 1	Condition 2	Condition 3	Condition 4
Feed water source	Settled water	Settled water	Settled water	Raw water
Average flux @ 20°C, gfd	24	24	35	27
Recovery, %	90	95	90	90
Maximum head				
psi	8.7	8.7	20	8.7
ft H ₂ O	20	20	46	20
Initial head loss				
TMP psi	5.5	5.5	7.4 (9.8 [§])	5.5
ft H ₂ O	12.7	12.7	17.0 (22.6 [§])	12.7
Estimated fouling rate				
psi/day	0.08	0.36	0.24	0.19
ft H ₂ O/day	0.18	0.83	0.55	0.45
Cleaning frequency [†] , days	41	9	48	16

[§] Day 5 TMP is used to calculate cleaning frequency since fouling rate more closely follows a linear trend after day 5.

[†] Cleaning Frequency = (Maximum Head – Initial TMP)/Fouling Rate, except in Condition 3 where the initial 5 days are included.

Figure 2: Hydraulic conditions 1 and 2 (settled water, flux = 40 L/hr.m² @20C)



Conditions 1 and 2, presented graphically in Figure 2, were both operated at a flux of 24 gfd (about 21.2 gpm) with the maximum head available assumed to be 20 ft of water. Flux values presented in Figure 2 and subsequent figures are adjusted to account for the variation of water viscosity due to changes in water temperature. Recovery was increased from 90 to 95 percent, when Condition 2 was initiated near the completion of Condition 1, by shortening the backwash frequency from once per hour to once every two hours. These pilot testing conditions may be related to full scale membrane filtration using gravity head by assuming operation is similar to that of granular media filtration where a constant head of water is maintained in the filter box, and flow through the membrane is varied by a rate of flow control valve.

The initial head loss due to a clean membrane at the flux tested for the assumed gravity conditions was 12.7 ft of water. Thus, the maximum head loss available for membrane fouling and other valve and piping losses was 7.3 ft. After this point, operation may continue, but operation will be in a declining rate rather than a constant flux mode, and chemical cleaning is required to restore the permeability of the membrane. Fouling rates averaged 0.18 ft/day for Condition 1 and 0.83 ft/day for Condition 2, and demonstrated the marked effect of recovery rate on membrane fouling.

Membrane fouling for Conditions 1 and 2, shown in Figure 2, appears to be linear to the point of maximum head loss (20 ft of water (8.7 psi)). While higher fluxes and shorter cleaning intervals reduce capital costs (Chellam, Serra, and Wiesner, 1998), operating costs increase. As mentioned earlier in this report, a minimum 30 day interval between chemical cleanings was used as a design guideline to strike a reasonable balance between capital and operating costs, and other operational preferences and concerns. As shown in Table 3 and Figure 2, Condition 1 meets this design criterion. However, the marked increase in membrane fouling recorded during Condition 2, when the recovery rate was increased from 90 to 95 percent, resulted in only a 9 day interval between chemical cleanings and failed to meet the 30 day criterion.

The custom membrane pilot was also operated at a higher pressure (*i.e.* 46 ft of water (about 20 psi)) and a higher flux (*i.e.* 35 gfd (about 31 gpm)) to simulate the hydraulic conditions produced with a pump driven system. The results of this simulation are shown as Condition 3 in Table 3 and Figure 3. As opposed to the assumed gravity filtration pilot testing condition, membrane fouling during the first five days of operation at the higher pressure was somewhat more abrupt, but became less significant as operation progressed. A linear correlation was assumed after day 5 to predict the chemical cleaning interval. As shown in Table 3, the fouling rate for Condition 3 is approximately 0.55 ft of water per day, which corresponds to a chemical cleaning interval of 48 days (including the initial 5 days), and meets the 30 day chemical cleaning interval criterion. The increased pressure allows more head for membrane fouling and a 46 percent increase in flux from 24 gfd to 35 gfd.

Conditions 1 through 3 described above used settled water as the feed water to the pilot plant. At the request of the participating utilities, an additional simulation (Condition 4) was performed using untreated Lake Michigan water as the feed water to the pilot plant. Condition 4 was operated assuming an available head of 20 ft of water (similar to Conditions 1 and 2), at an average flux rate of 27 gfd and a recovery rate of 90 percent. The membrane fouled in 16 days, which equates to a fouling rate of 0.45 ft of water per day and fails to meet the criterion of 30 days between chemical cleanings. Results of the simulation of Condition 4 are presented in Table 3 and Figure 4. Based on this limited testing, operation of the membrane with raw water would likely entail the use of additional pressure developed with a pump.

Figure 3: Hydraulic condition 3 (settled water, flux = 60 L/hr.m² @20C)

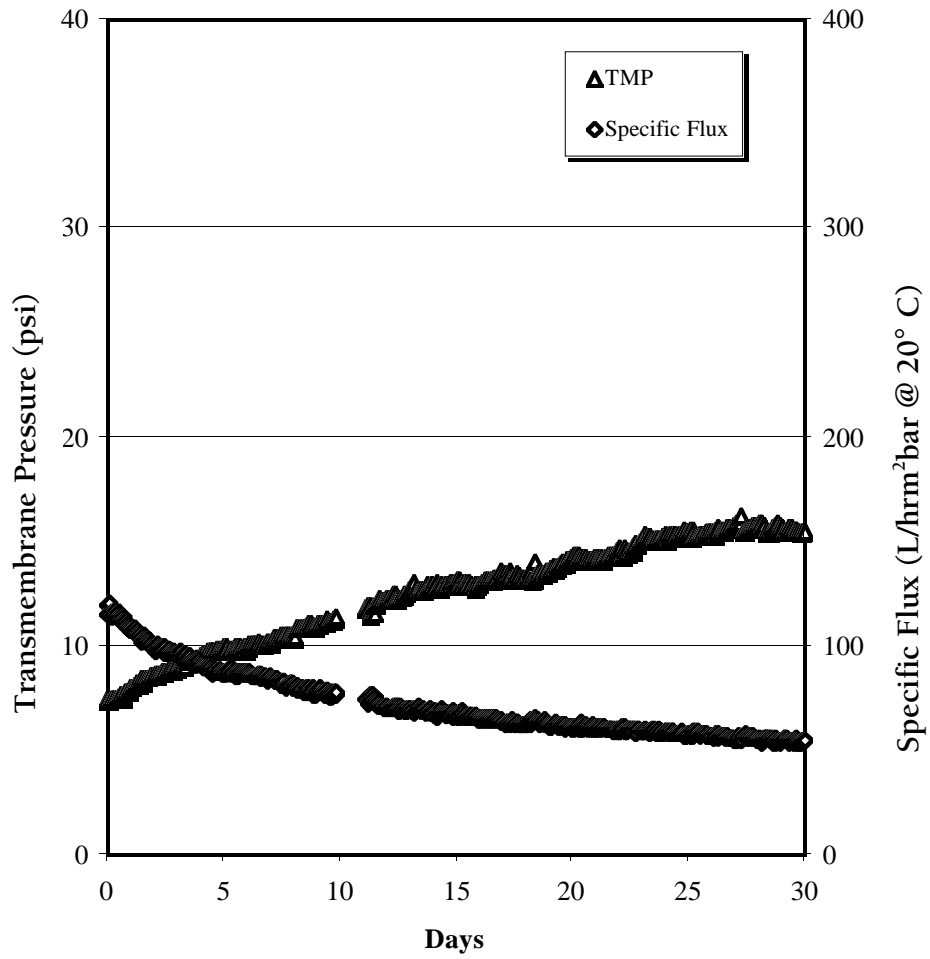
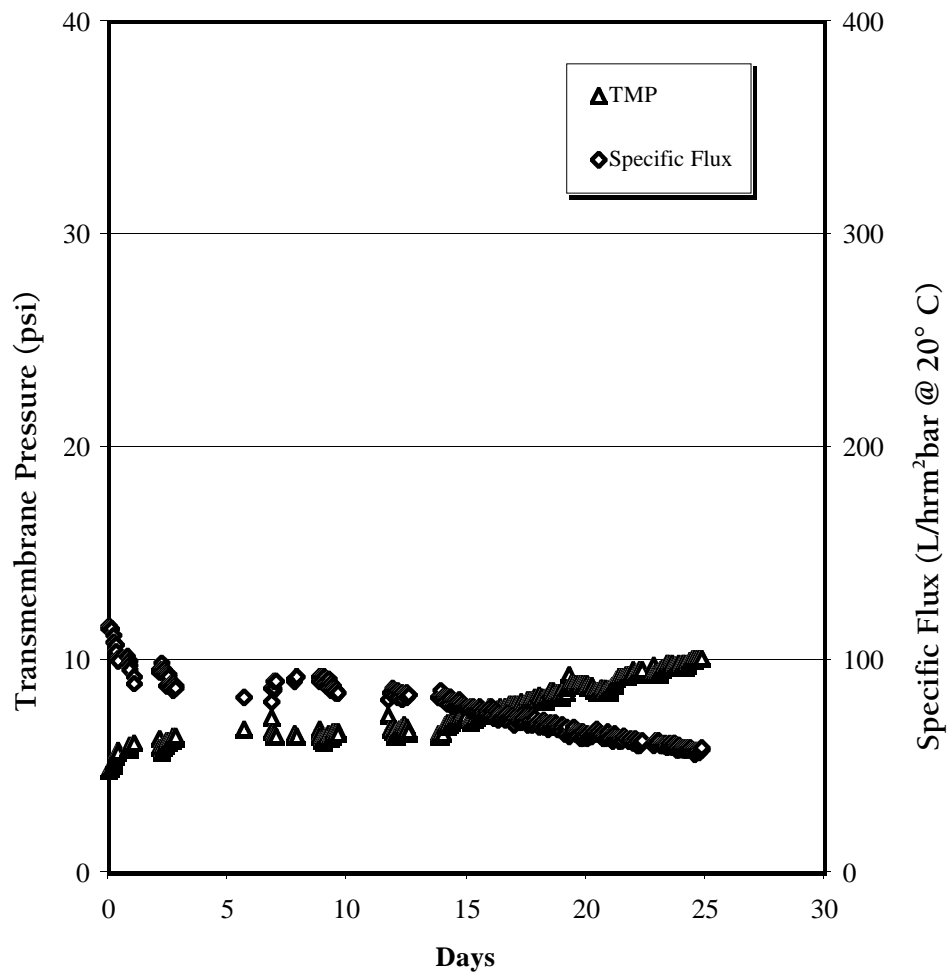


Figure 4: Hydraulic condition 4 (raw Lake Michigan water, flux = 40 L/hr.m² @20C)



Feed and Permeate Water Quality Data

Water quality data recorded over the entire course of the pilot testing simulations are summarized in Table 4. Permeate turbidities recorded during each of the hydraulic conditions averaged below 0.01 NTU and are well below the 0.30 NTU turbidity standard contained in the IESWTR which will govern turbidity levels beginning December 2001 at Sheboygan and other surface WTPs serving 10,000 or more people. The number and sizes of particles in the permeate stream also were recorded as a method to monitor and ensure membrane integrity throughout the testing period. Particle counts averaged 0 counts/ml in all size ranges with the exception of the 2 to 5 μm range, which averaged 0.02 counts/ml. Particle counts ranged from a minimum of 0 counts/ml in each of the five size ranges tested to maximum counts ranging from 0.33 to 2.83 counts/ml in the various size ranges. Given the level of particle removal shown by the data in Table 4, it is evident that the membrane remained intact and provided a barrier to microbial pathogens throughout the 120 day pilot testing period. Heterotrophic plate counts (HPCs) were also measured in the feed and permeate streams as another method to verify membrane integrity. No heterotrophic bacteria were measured in the permeate stream in Conditions 1 through 3 because the settled water is prechlorinated and the bacteria should have been inactivated prior to the membrane process. When the raw (*i.e.* unchlorinated) Lake Michigan water was treated in Condition 4, no heterotrophic bacteria were detected in the membrane permeate, which demonstrates that the membrane remained intact and provided a barrier to pathogens throughout the four months of testing.

Total organic carbon (TOC) concentrations and absorption of ultraviolet radiation (UV254) were measured in the settled water and in the membrane treated water to quantify and characterize the organic matter influent to the membrane. Settled water TOC and UV254 data, presented in Table 4, show that dissolved organic carbon was present in relatively low concentrations with average values of only 1.88 mg/L and 0.019 cm^{-1} , respectively. On average, the UF membrane process removed only 8 percent of the TOC and 21 percent of the organic fraction contributing to UV254. Removal of the TOC and UV254 absorption is source water dependent since the molecular size and composition of TOC varies from one water body to another. A possible explanation for the larger percentage of UV254 removed may be that the UV absorbing organics (*i.e.* TOC containing double and triple carbon bonds) were primarily associated with the larger TOC molecules (*i.e.* the 8 percent removed) which were absorbed onto or did not pass through the membrane. Another explanation may involve ferrous iron and reducing agents such as chloramines, ozone, and thiosulfate which have been noted to interfere with UV measurements (American Public Health Association (ADHA), 1995). While it is unlikely that these constituents were present in concentrations high enough to produce an interference, it may be possible that the feed water UV measurements were uncharacteristically high due to inorganic interferences to UV absorption, thereby resulting in a higher removal percentage.

Estimated Construction Costs

Construction costs were estimated for the upgrade or retrofit of the Sheboygan WTP with: the custom design UF membrane system, an ozone disinfection system, and a proprietary UF membrane system. The estimates assume a WTP capacity of 34 mgd. The accuracy of the costs is estimated to be in the range of -15 to +30 percent of actual costs. Cost estimates are based on present day (*i.e.* June 2000) costs and do not include any allowances

for inflation, contingencies, or engineering. Additional assumptions specific to each alternative are described below.

Custom Design UF Membranes

The use of the custom design UF membrane system at Sheboygan will assume the use of settled water as the feed source to the membranes because of the more rapid rate of fouling shown when treating raw Lake Michigan water. Based on a preliminary inspection of the water surface elevations in the settled water channel and in the clearwell, it is assumed no pumping will be required to implement the custom design membrane system at Sheboygan and to supply the current 34 mgd capacity.

Table 4: Feed and permeate water quality data

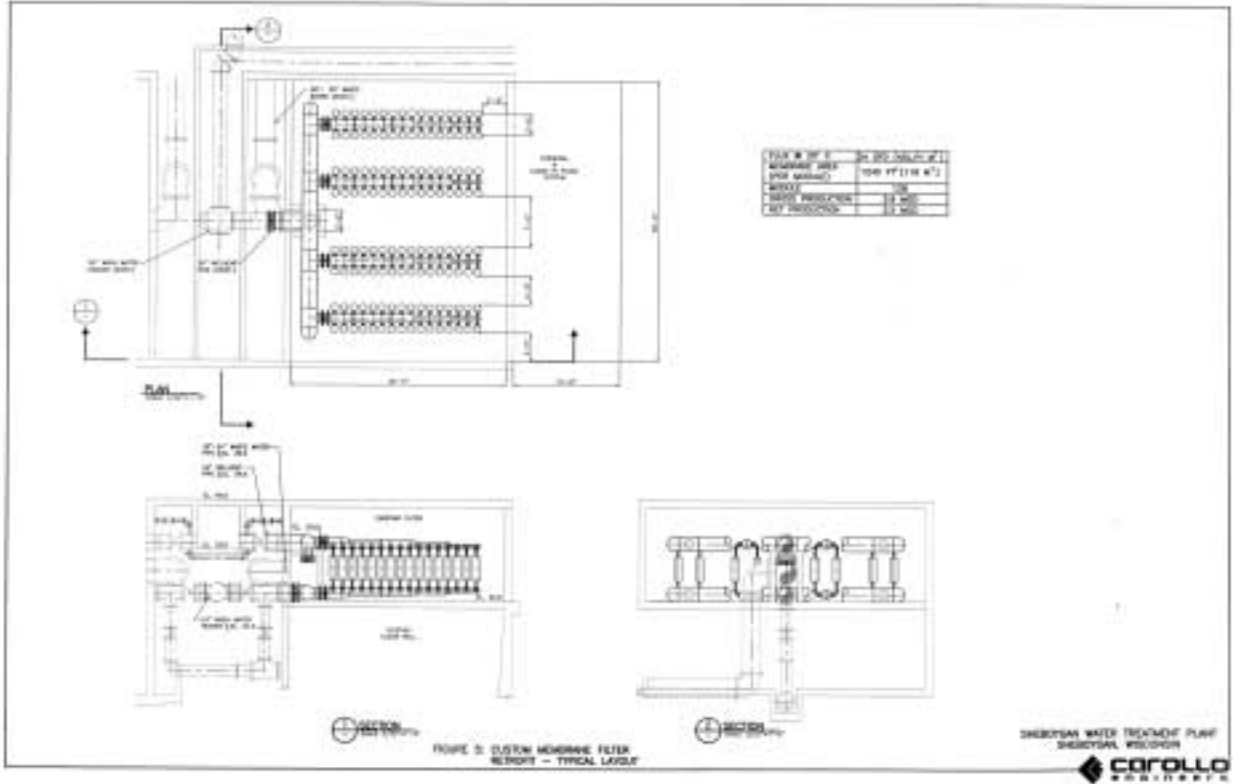
	Turbidity (NTU)		Permeate Particle Counts (#/ml)				
	Feed	Permeate	2-5 μm	5-7 μm	7-10 μm	10-15 μm	> 15 μm
Number of samples	72	71	86,700	86,700	86,700	86,700	86,700
Average	1.04	0.01	0.02	0.00	0.00	0.00	0.00
Standard deviation	0.31	0.00	0.13	0.01	0.01	0.02	0.02
Minimum	0.57	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	2.2	0.01	2.83	0.33	0.43	1.28	1.28

Table 4 (continued): Feed and permeate water quality data

	HPC (#/100 ml)		TOC (mg/L)		UV ₂₅₄ (cm ⁻¹)	
	Feed	Permeate	Feed	Permeate	Feed	Permeate
Number of samples	35	24	20	20	19	19
Average	0.1	0.0	1.88	1.73	0.019	0.015
Standard deviation	0.2	0.0	0.27	0.21	0.006	0.004
Minimum	0.0	0.0	1.59	1.48	0.013	0.010
Maximum	1.0	0.0	2.45	2.10	0.029	0.021

A possible configuration showing the retrofit of the custom design membrane system into an existing filter box (i.e. Filter 10) at Sheboygan is shown in Figure 5.

Figure 5: Custom membrane filter retrofit



The estimated construction cost to implement the custom design UF membrane system at the Sheboygan WTP is \$ 12,000,000. This estimate assumes the continued use of existing rate-of-flow controllers, valves, piping, and the backwash pump.

Ozone Disinfection System

The Sheboygan Water Utility commissioned an engineering study in Fall 1998 to assess the feasibility and costs of implementing an ozone disinfection system at the WTP. The study determined that it is feasible to implement ozone disinfection facilities and that pre-ozonation (i.e. ozonating the raw water ahead of the pretreatment processes) is the best concept to implement ozone disinfection into the existing process train at the WTP site. The proposed system includes the use of two process trains each comprised of a horizontal, baffled, counter-flow bubble diffuser contactor with eight cells to provide the required diffusion and reaction time. The contactor is sized for a hydraulic retention time of 22 minutes at the design capacity of 34 mgd and would be equipped with the ozone generation and feed equipment to effect a 2 log inactivation of *Cryptosporidium* oocysts.

The construction cost estimated in 1998 was increased by 5 percent for inflation to yield the present day construction cost estimate of \$ 5,100,000.

Proprietary UF Membrane System

Implementation of a new, proprietary UF membrane system at Sheboygan could involve the selection of a packaged system available from several manufacturers. While it is possible that the membrane units could be located within an existing building at the WTP, the following analysis will assume a new building will be constructed and that raw water rather than settled water will be used as the feed water source. Other key system components include:

- An influent water pumping station (i.e. six, variable frequency drive pumps with a maximum discharge head of 25 psig)
- Two, backwashable prefilters
- UF, hollow fiber, pressure membranes (14 racks of 48 modules per rack) manufactured of a polysulfone material with recirculation booster pumps and associated piping
- Two backwash pumps and two chemical cleaning storage and feeding tank
- An instrumentation and control system

The construction cost to implement the proprietary UF membrane system at Sheboygan is estimated at \$27,000,000. The estimate is based upon a cost analysis of a recent UF membrane installation (i.e. Year 2000) at a 32 mgd WTP in northeastern Wisconsin.

The construction cost estimates for the three alternatives are summarized below.

<u>Water Treatment Process</u>	<u>Construction Cost</u>
Custom design membrane system	\$12,000,000
Ozone disinfection system	\$5,100,000
Proprietary UF membrane system	\$27,000,000

Operations and Maintenance Costs

Annual operations and maintenance (O&M) costs for each of the three alternatives described above are summarized in Table 5. Costs are based on operating data and information provided by Sheboygan Water Utility staff, and on information developed in other recent studies. An average annual water demand of 16 mgd is assumed.

Table 5: O&M cost summary

	Customdesign membrane system (\$/year)	Ozone disinfection system (\$/year)	Proprietary UF membrane system (\$/year)
Personnel	520,000	520,000	520,000
Existing WTP operations ^a	470,000	470,000	-----
Low and high service pumping ^b	-----	-----	250,000
Ozone	-----	100,000 ^c	-----
Membrane pumping	-----	-----	30,000
Chemical cleaning chemicals	10,000	-----	10,000
Membrane replacement	430,000 ^d	-----	500,000 ^e
Total	1,430,000	1,090,000	1,310,000

a Includes costs for electricity (including low and high service pumping), natural gas, and water treatment chemicals.

b Assumes low and high service pumping costs stay the same and are independent from the UF membrane treatment process.

c Ozone O&M costs taken from *Engineering Study for Ozone Disinfection* (1998), increased for inflation and a larger annual demand, and rounded to the nearest significant figure.

d Assumes custom membrane replacement costs of \$3,000 per module every seven years. It is estimated that the installation will require 1,210 modules. The future costs were annualized assuming a 6 percent interest rate.

e Assumes proprietary UF membrane system replacement costs of \$4,500 per module every eight years. It is estimated that the installation will require 1,088 modules. The future costs were annualized assuming a 6 percent interest rate.

Power Component Analysis

The Center also requested that an estimate be made of the energy savings which could result from the use of a gravity versus a pumped membrane system. Energy savings may be estimated by pumping requirements. Proprietary membrane systems require an average feed pressure on the order of 15 to 20 psi over the course of a filtration cycle (Electric Power Research Institute (EPRI), 1999), while the proposed alternative "gravity"

membrane system uses the head pressure already available through existing plant hydraulics. For this example, an average feed pressure of 15 psi will be used to estimate pumping power requirements using Equation 1:

Equation 1: Pump horse power

$$hp = \frac{\Delta p Q}{1714}$$

Where Δp is the feed pressure required (psi) and Q is the flow (gpm).

Assumptions:

- The annual average day demand experienced at Sheboygan is 16 mgd or 11,120 gpm.
- The WTP is operated 24 hours a day.
- The cost of electricity is \$ 0.045/kW-hr.

Using these parameters, the proprietary (pumped) UF membrane system uses an additional 109 kW-hr per million gallons of water produced or 636,000 kW-hr per year when compared to the gravity membrane system. This equates to an estimated, additional energy cost per year of \$28,600 or expressed in a different way, about \$4.90 per million gallons of water.

Emerging Technology—Ultraviolet Radiation

Another emerging technology for the inactivation of microbial pathogens is ultraviolet (UV) radiation which has been found to be effective at inactivating vegetative and sporous forms of bacteria, viruses, and other pathogenic microorganisms. Unlike most other disinfectants, UV radiation does not inactivate microorganisms by chemical interaction. Destruction of microorganisms by UV radiation occurs when the UV energy is absorbed by the genetic material of the cells which causes a photochemical reaction that alters molecular components essential to cell function. As UV rays penetrate the cell wall of the microorganism, the energy reacts with nucleic acids and other vital cell components, resulting in injury or death of the exposed cells. Although all microorganisms are susceptible to UV radiation, the sensitivity of organisms varies depending on their resistance to the penetration of the UV energy. The chemical composition of the cell wall and its thickness determine the relative resistance of an organism. An organism's resistance is measured by the time needed to kill a certain percentage of organisms by a specific UV dose.

While it appears that UV radiation is exceptional for the disinfection of microorganisms such as bacteria and viruses, research published in the late 1980s and early 1990s reported UV doses required to inactivate larger protozoa such as *Giardia* cysts and *Cryptosporidium* oocysts were several times higher than for bacteria and virus inactivation. More recent research measuring inactivation using mouse infectivity methods has shown that UV radiation systems (i.e. pulsed UV and medium-pressure, continuous wave systems) were effective at inactivating *Cryptosporidium* oocysts at relatively low doses (i.e. 20 to 50 milliwatt seconds per square centimeter (mW-s/cm²)). UV radiation disinfection systems for drinking water are used in over 30 WTPs in Europe and a system was recently installed on a 14 mgd surface water source in Michigan. Several additional studies are underway (including one funded by the Center and other participating utilities) and will provide additional data upon which the EPA can base a decision regarding the effectiveness of UV for the inactivation of *Giardia* cysts and

Cryptosporidium oocysts, and develop CT values for log inactivation of these microbes. Some researchers predict the EPA will include new guidelines for the use of this technology with the promulgation of the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) scheduled for May 2002.

Based on conversations with vendors and information about the systems gleaned from a recent (March 2000) tour of existing installations in Europe, construction costs for implementing a UV radiation disinfection system at Sheboygan for a flow of 34 mgd are estimated at \$ 2,400,000. Operations and maintenance costs for this component are estimated in the range of \$0.50 to \$1.50/million gallons produced at Sheboygan or about \$3,000 to \$9,000 per year. Estimates of construction and O&M costs for implementation of this technology are included here for information purposes in the event that the EPA will allow some or comparable credit to ozone disinfection for the inactivation of *Cryptosporidium* oocysts and other pathogens.

Conclusions

The work presented in this paper is the first effort to operate and evaluate UF membranes at pressures which could allow their implementation in lieu of granular media filtration within the hydraulic gradeline existing at some conventional treatment plants. Successful operation of a custom UF membrane treating settled water was demonstrated over the course of 30 days of pilot testing at a flux of 24 gfd with a head of 20 ft of water. This low head, low flux approach to membrane system design offers water utilities seeking to maximize the use of existing infrastructure a new alternative for facility retrofit. The custom UF membranes were also operated at higher pressures produced with a pump and successfully operated treating settled water at a flux of 35 gfd for 30 days at a maximum pressure of 20 psi.

Raw Lake Michigan water was tested at a flux of 27 gfd with a head of 20 ft of water and fouled the membrane within 16 days. This more rapid fouling rate failed to meet the 30 day interval between chemical cleanings specified during the study. Based upon this limited testing, operation of the membrane with raw water would likely require the use of additional pressure provided by a pump.

Construction cost estimates for the upgrade or retrofit of the 34 mgd Sheboygan WTP predict that the implementation of ozone disinfection to address the inactivation of chlorine-resistant pathogens in the surface water source is less expensive than either of the membrane technologies tested. The use of ozone may not be feasible at some WTPs because of water quality concerns (e.g. disinfection by-products), incompatibility with existing facilities or process constraints

(e.g. existing hydraulic gradelines), and high operating costs which may be required to meet the inactivation conditions still being developed by the federal government. It may be possible to implement the custom membrane system at certain plants at roughly 40 percent of the cost of proprietary UF membrane systems currently available. These results may hold promise for the implementation of UF membranes at surface WTPs which heretofore have not considered membranes due to the high cost of the proprietary, modular based membrane systems.

Membranes offer an attractive alternative for providing a virtually absolute barrier to pathogens. As opposed to conventional chemical disinfection processes where some degree of short circuiting and inefficiency is inevitable, an intact membrane offers a virtually absolute physical barrier to pathogens. This was demonstrated during pilot tests where particle counts in the membrane permeate stream averaged 0 counts/ml across all size ranges except the 2 – 5 μm range where counts averaged only 0.02 counts/ml.

Recommendations

Additional studies are recommended to confirm project results:

- At other locations with other water sources
- With microbial challenge tests
- With different membrane characteristics

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- With other modifications to the pilot plant unit (*e.g.* recirculation pumping) to optimize chemical cleaning methods and to explore the effect of other pretreatment processes and chemicals (*e.g.* ferric coagulants, lime, and PAC) on membrane performance

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Appendix A: Abbreviations

BAF	biologically active filtration
CaCO ₃	calcium carbonate
cm	centimeter
counts/ml	particle counts recorded per milliliter of fluid
CT	concentration multiplied by time
DBP	disinfection by-product/s
EPA	United States Environmental Protection Agency
ft	foot/feet
ft ²	square foot/feet
ft/day	feet per day
ft/s	feet per second
ftH ₂ O/day	feet of water per day
gfd	gallons per square foot per day
gpm	gallons per minute
H ₂ O	water
HPC	heterotrophic plate count
hp	horsepower
IESWTR	Interim Enhanced Surface Water Treatment Rule
in	inch
kW-hr	kilowatt hour/s
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
m ²	square meter
MCL	maximum contaminant level
MF	microfiltration
mg/L	milligram per liter
mgd	million gallons per day
ml	milliliter
mm	millimeter
mW-s/cm ²	milliwatt seconds per square centimeter
NOM	natural organic matter
NTU	nephelometric turbidity unit
O&M	operations and maintenance
p	pressure
PAC	powdered activated carbon
pK _a	negative logarithm of the equilibrium constant K _a
PLC	programmable logic controller
psi	pound/s per square inch
psi/day	pound/s per square inch per day
psig	pounds per square inch gage
Q	flow rate
SWTR	Surface Water Treatment Rule
TMP	transmembrane pressure
TOC	total organic carbon
UF	ultrafiltration

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UV	ultraviolet light
UV ₂₅₄	ultraviolet light absorbance at 254 nanometers
WI	Wisconsin
WTP	water treatment plant
@	at
\$	dollars
\$/year	dollars per year
µg/L	micrograms per liter
µm	micron
°C	degrees Celsius
°F	degrees Fahrenheit
#/ml	number per milliliter
★	change in a parameter



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