



Wastewater Management Fact Sheet

Membrane Bioreactors

INTRODUCTION

The technologies most commonly used for performing secondary treatment of municipal wastewater rely on microorganisms suspended in the wastewater to treat it. Although these technologies work well in many situations, they have several drawbacks, including the difficulty of growing the right types of microorganisms and the physical requirement of a large site. The use of microfiltration membrane bioreactors (MBRs), a technology that has become increasingly used in the past 10 years, overcomes many of the limitations of conventional systems. These systems have the advantage of combining a suspended growth biological reactor with solids removal via filtration. The membranes can be designed for and operated in small spaces and with high removal efficiency of contaminants such as nitrogen, phosphorus, bacteria, biochemical oxygen demand, and total suspended solids. The membrane filtration system in effect can replace the secondary clarifier and sand filters in a typical activated sludge treatment system. Membrane filtration allows a higher biomass concentration to be maintained, thereby allowing smaller bioreactors to be used.

APPLICABILITY

For new installations, the use of MBR systems allows for higher wastewater flow or improved treatment performance in a smaller space than a conventional design, i.e., a facility using secondary clarifiers and sand filters. Historically, membranes have been used for smaller-flow systems due to the high capital cost of the equipment and high operation and maintenance (O&M) costs. Today however, they are receiving increased use in larger systems. MBR systems are also well suited for some industrial and commercial applications. The high-quality effluent produced by MBRs makes them particularly applicable to reuse applications and for surface

water discharge applications requiring extensive nutrient (nitrogen and phosphorus) removal.

ADVANTAGES AND DISADVANTAGES

The advantages of MBR systems over conventional biological systems include better effluent quality, smaller space requirements, and ease of automation. Specifically, MBRs operate at higher volumetric loading rates which result in lower hydraulic retention times. The low retention times mean that less space is required compared to a conventional system. MBRs have often been operated with longer solids residence times (SRTs), which results in lower sludge production; but this is not a requirement, and more conventional SRTs have been used (Crawford et al. 2000). The effluent from MBRs contains low concentrations of bacteria, total suspended solids (TSS), biochemical oxygen demand (BOD), and phosphorus. This facilitates high-level disinfection. Effluents are readily discharged to surface streams or can be sold for reuse, such as irrigation.

The primary disadvantage of MBR systems is the typically higher capital and operating costs than conventional systems for the same throughput. O&M costs include membrane cleaning and fouling control, and eventual membrane replacement. Energy costs are also higher because of the need for air scouring to control bacterial growth on the membranes. In addition, the waste sludge from such a system might have a low settling rate, resulting in the need for chemicals to produce biosolids acceptable for disposal (Hermanowicz et al. 2006). Fleischer et al. 2005 have demonstrated that waste sludges from MBRs can be processed using standard technologies used for activated sludge processes.

MEMBRANE FILTRATION

Membrane filtration involves the flow of water-containing pollutants across a membrane. Water permeates through the membrane into a separate channel for recovery (Figure 1). Because of the cross-flow movement of water and the waste constituents, materials left behind do not accumulate at the membrane surface but are carried out of the system for later recovery or disposal. The water passing through the membrane is called the *permeate*, while the water with the more-concentrated materials is called the *concentrate* or *retentate*.

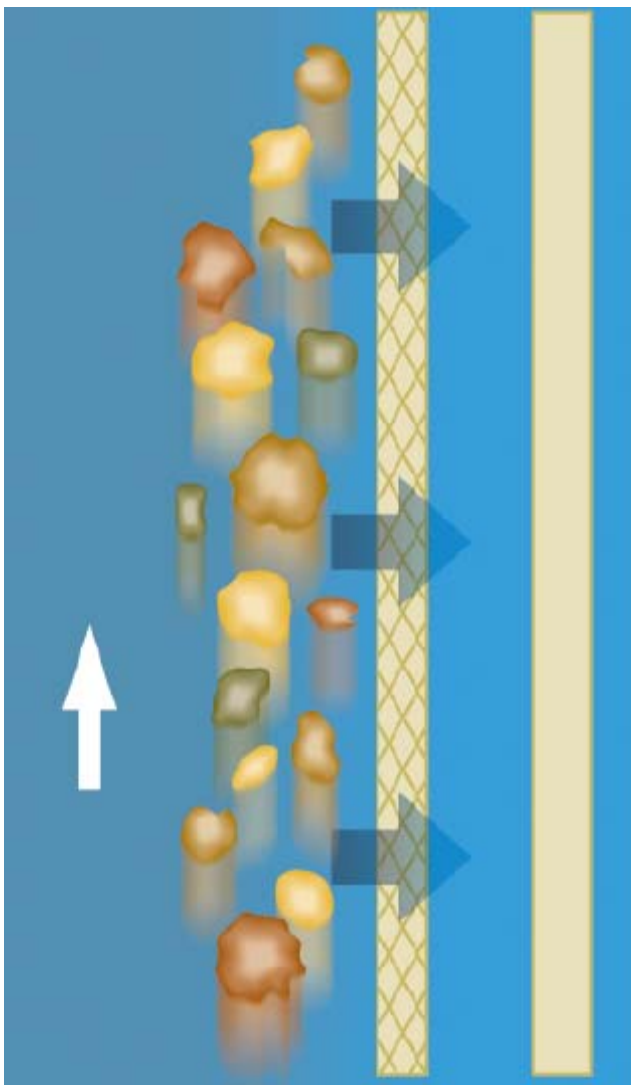


Figure 1. Membrane filtration process (Image from Siemens/U.S. Filter)

Membranes are constructed of cellulose or other polymer material, with a maximum pore size set during the manufacturing process. The require-

ment is that the membranes prevent passage of particles the size of microorganisms, or about 1 micron (0.001 millimeters), so that they remain in the system. This means that MBR systems are good for removing solid material, but the removal of dissolved wastewater components must be facilitated by using additional treatment steps.

Membranes can be configured in a number of ways. For MBR applications, the two configurations most often used are hollow fibers grouped in bundles, as shown in Figure 2, or as flat plates. The hollow fiber bundles are connected by manifolds in units that are designed for easy changing and servicing.



Figure 2. Hollow-fiber membranes (Image from GE/Zenon)

DESIGN CONSIDERATIONS

Designers of MBR systems require only basic information about the wastewater characteristics, (e.g., influent characteristics, effluent requirements, flow data) to design an MBR system. Depending on effluent requirements, certain supplementary options can be included with the MBR system. For example, chemical addition (at various places in the treatment chain, including: before the primary settling tank; before the secondary settling tank [clarifier]; and before the MBR or final filters) for phosphorus removal can be included in an MBR system if needed to achieve low phosphorus concentrations in the effluent.

MBR systems historically have been used for small-scale treatment applications when portions of the treatment system were shut down and the

wastewater routed around (or bypassed) during maintenance periods.

However, MBR systems are now often used in full-treatment applications. In these instances, it is recommended that the installation include one additional membrane tank/unit beyond what the design would nominally call for. This “N plus 1” concept is a blend between conventional activated sludge and membrane process design. It is especially important to consider both operations and maintenance requirements when selecting the number of units for MBRs. The inclusion of an extra unit gives operators flexibility and ensures that sufficient operating capacity will be available (Wallis-Lage et al. 2006). For example, bioreactor sizing is often limited by oxygen transfer, rather than the volume required to achieve the required SRT—a factor that significantly affects bioreactor numbers and sizing (Crawford et al. 2000).

Although MBR systems provide operational flexibility with respect to flow rates, as well as the ability to readily add or subtract units as conditions dictate, that flexibility has limits. Membranes typically require that the water surface be maintained above a minimum elevation so that the membranes remain wet during operation. Throughput limitations are dictated by the physical properties of the membrane, and the result is that peak design flows should be no

more than 1.5 to 2 times the average design flow. If peak flows exceed that limit, either additional membranes are needed simply to process the peak flow, or equalization should be included in the overall design. The equalization is done by including a separate basin (external equalization) or by maintaining water in the aeration and membrane tanks at depths higher than those required and then removing that water to accommodate higher flows when necessary (internal equalization).

DESIGN FEATURES

Pretreatment

To reduce the chances of membrane damage, wastewater should undergo a high level of debris removal prior to the MBR. Primary treatment is often provided in larger installations, although not in most small to medium sized installations, and is not a requirement. In addition, all MBR systems require 1- to 3-mm-cutoff fine screens immediately before the membranes, depending on the MBR manufacturer. These screens require frequent cleaning. Alternatives for reducing the amount of material reaching the screens include using two stages of screening and locating the screens after primary settling.

Membrane Location

MBR systems are configured with the mem-

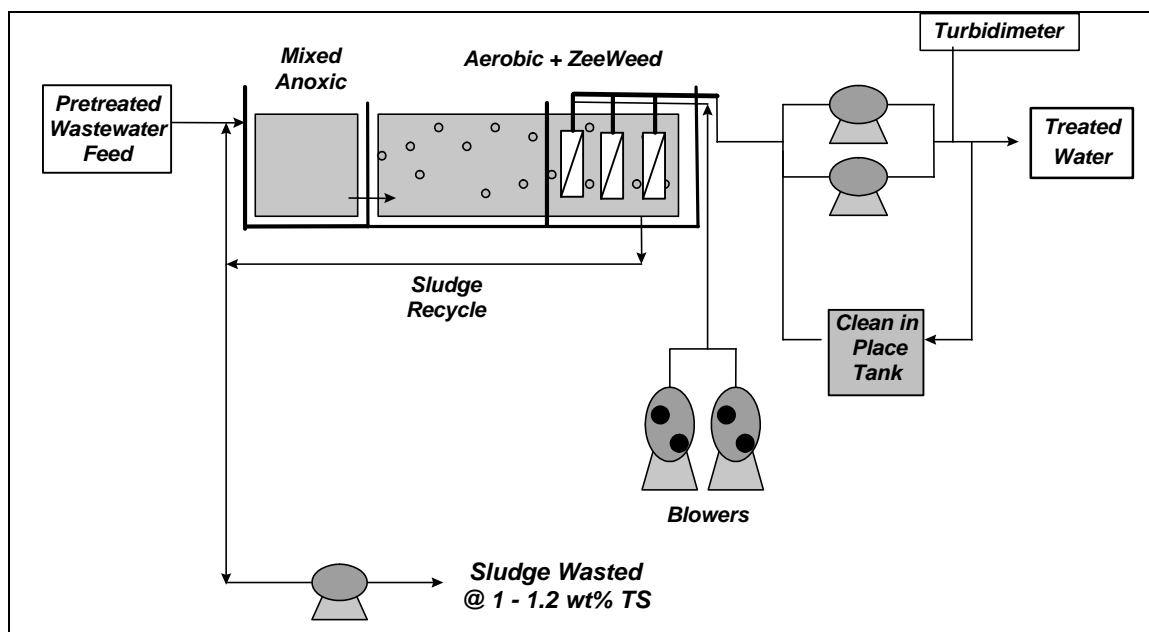


Figure 3. Immersed membrane system configuration (Image from GE/Zenon)

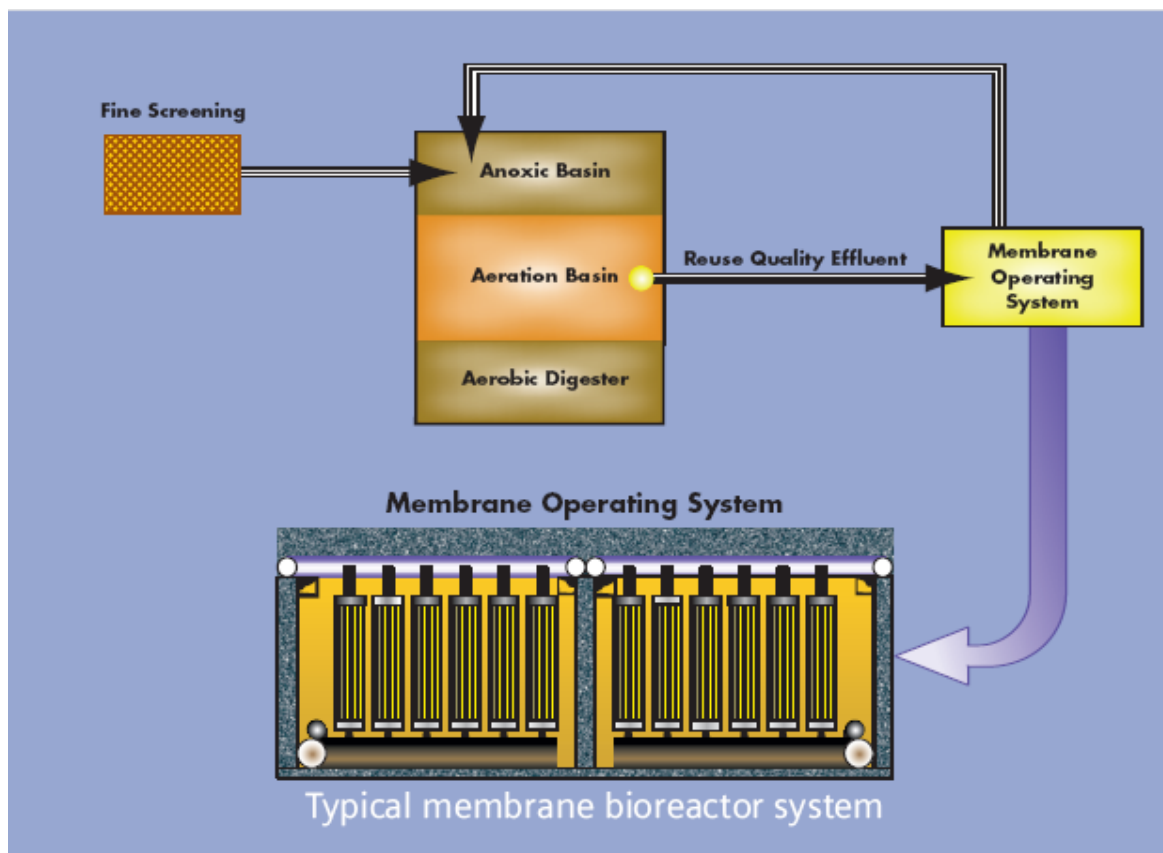


Figure 4. External membrane system configuration (Image from Siemens/U.S. Filter)

branes actually immersed in the biological reactor or, as an alternative, in a separate vessel through which mixed liquor from the biological reactor is circulated. The former configuration is shown in Figure 3; the latter, in Figure 4.

Membrane Configuration

MBR manufacturers employ membranes in two basic configurations: hollow fiber bundles and plate membranes. Siemens/U.S.Filter's Memjet and Memcor systems, GE/Zenon's ZeeWeed and ZenoGem systems, and GE/Ionics' system use hollow-fiber, tubular membranes configured in bundles. A number of bundles are connected by manifolds into units that can be readily changed for maintenance or replacement. The other configuration, such as those provided by Kubota/Enviroquip, employ membranes in a flat-plate configuration, again with manifolds to allow a number of membranes to be connected in readily changed units. Screening requirements for both systems differ: hollow-fiber membranes typically require 1- to 2-mm screening, while

plate membranes require 2- to 3-mm screening (Wallis-Lage et al. 2006).

System Operation

All MBR systems require some degree of pumping to force the water flowing through the membrane. While other membrane systems use a pressurized system to push the water through the membranes, the major systems used in MBRs draw a vacuum through the membranes so that the water outside is at ambient pressure. The advantage of the vacuum is that it is gentler to the membranes; the advantage of the pressure is that throughput can be controlled. All systems also include techniques for continually cleaning the system to maintain membrane life and keep the system operational for as long as possible. All the principal membrane systems used in MBRs use an air scour technique to reduce buildup of material on the membranes. This is done by blowing air around the membranes out of the manifolds. The GE/Zenon systems use air scour, as well as a back-pulsing technique, in which permeate is occasionally pumped back

into the membranes to keep the pores cleared out. Back-pulsing is typically done on a timer, with the time of pulsing accounting for 1 to 5 percent of the total operating time.

Downstream Treatment

The permeate from an MBR has low levels of suspended solids, meaning the levels of bacteria, BOD, nitrogen, and phosphorus are also low. Disinfection is easy and might not be required, depending on permit requirements..

The solids retained by the membrane are recycled to the biological reactor and build up in the system. As in conventional biological systems, periodic sludge wasting eliminates sludge buildup and controls the SRT within the MBR system. The waste sludge from MBRs goes through standard solids-handling technologies for thickening, dewatering, and ultimate disposal. Hermanowicz et al. (2006) reported a decreased ability to settle in waste MBR sludges due to increased amounts of colloidal-size particles and filamentous bacteria. Chemical addition increased the ability of the sludges to settle. As more MBR facilities are built and operated, a more definitive understanding of the characteristics of the resulting biosolids will be achieved. However, experience to date indicates that conventional biosolids processing unit operations are also applicable to the waste sludge from MBRs.

Membrane Care

The key to the cost-effectiveness of an MBR system is membrane life. If membrane life is curtailed such that frequent replacement is required, costs will significantly increase. Membrane life can be increased in the following ways:

- Good screening of larger solids before the membranes to protect the membranes from physical damage.
- Throughput rates that are not excessive, i.e., that do not push the system to the limits of the design. Such rates reduce the amount of material that is forced into the membrane and thereby reduce the amount that has to be re-

moved by cleaners or that will cause eventual membrane deterioration.

- Regular use of mild cleaners. Cleaning solutions most often used with MBRs include regular bleach (sodium) and citric acid. The cleaning should be in accord with manufacturer-recommended maintenance protocols.

Membrane Guarantees

The length of the guarantee provided by the membrane system provider is also important in determining the cost-effectiveness of the system. For municipal wastewater treatment, longer guarantees might be more readily available compared to those available for industrial systems. Zenon offers a 10-year guarantee; others range from 3 to 5 years. Some guarantees include cost prorating if replacement is needed after a certain service time. Guarantees are typically negotiated during the purchasing process. Some manufacturers' guarantees are tied directly to screen size: longer membrane warranties are granted when smaller screens are used (Wallis-Lage et al. 2006). Appropriate membrane life guarantees can be secured using appropriate membrane procurement strategies (Crawford et al. 2002).

SYSTEM PERFORMANCE

Siemens/U.S. Filter Systems

Siemens/U.S.Filter offers MBR systems under the Memcor and Memjet brands. Data provided by U.S. Filter for its Calls Creek (Georgia) facility are summarized below. The system, as Calls Creek retrofitted it, is shown in Figure 5. In essence, the membrane filters were used to replace secondary clarifiers downstream of an Orbal oxidation ditch. The system includes a fine screen (2-mm cutoff) for inert solids removal just before the membranes.

The facility has an average flow of 0.35 million gallons per day (mgd) and a design flow of 0.67 mgd. The system has 2 modules, each containing 400 units, and each unit consists of a cassette with manifold-connected membranes. As shown in Table 1, removal of BOD, TSS, and ammonia-nitrogen is excellent; BOD and TSS in the effluent are around the detection limit. Phosphorus is also removed well in the system, and the effluent

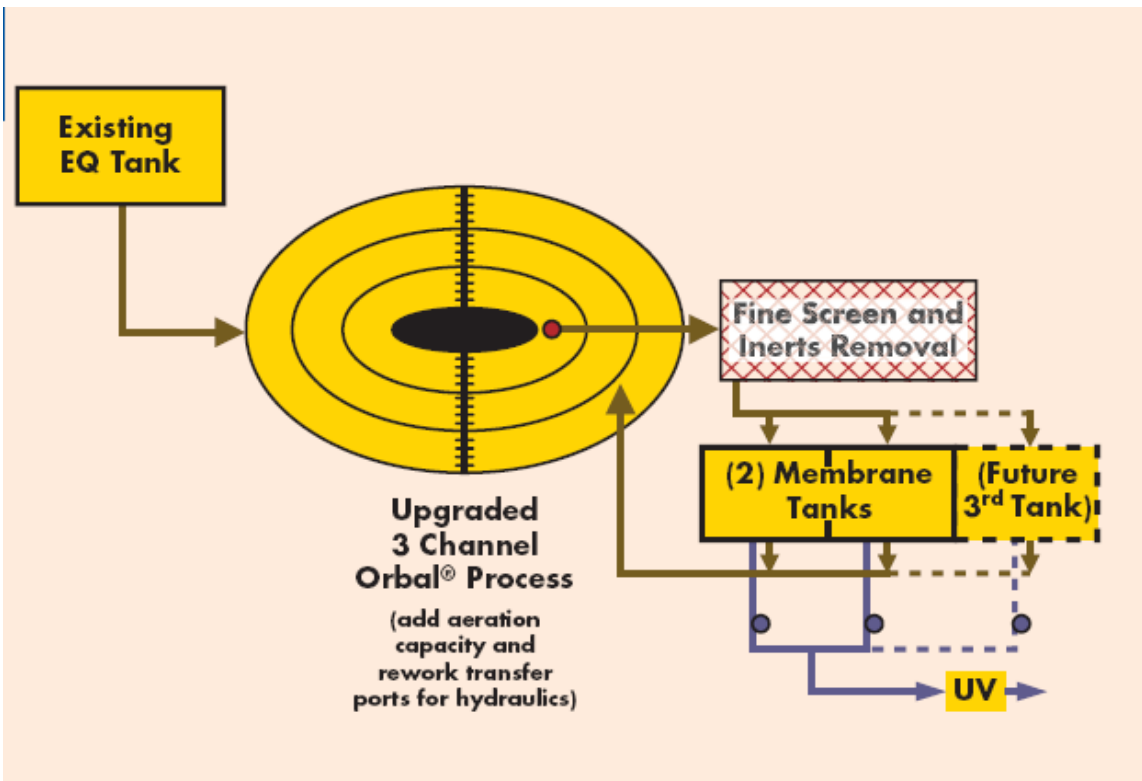


Figure 5. Calls Creek flow diagram (courtesy of Siemens/U.S. Filter)

Table 1.
Calls Creek results 2005

Parameter	Influent	Effluent		
	Average	Average	Max Month	Min Month
Flow (mgd)	0.35	--	0.44	0.26
BOD (mg/L)	145	1	1	1
TSS (mg/L)	248	1	1	1
Ammonia-N (mg/L)	14.8	0.21	0.72	0.10
P (mg/L)	0.88	0.28	0.55	0.12
Fecal coliforms (#/100 mL)	--	14.2	20	0
Turbidity (NTU)	--	0.30	1.31	0.01

has very low turbidity. The effluent has consistently met discharge limits.

Zenon Systems

General Electric/Zenon provides systems under the ZenoGem and ZeeWeed brands. The ZeeWeed brand refers to the membrane, while ZenoGem is the process that uses ZeeWeed.

Performance data for two installed systems are shown below.

Cauley Creek, Georgia. The Cauley Creek facility in Fulton County, Georgia, is a 5-mgd wastewater reclamation plant. The system includes biological phosphorus removal, mixed liquor surface wasting, and sludge thickening using a ZeeWeed system to minimize the required volume of the aerobic digester, according to information provided by GE. Ultraviolet disinfection is employed to meet regulatory limits. Table 2 shows that the removal for all parame-

Table 2.
Cauley Creek, Georgia, system performance

Parameter	Influent Average	Effluent		
		Average	Max Month	Min Month
Flow (mgd)	4.27	--	4.66	3.72
BOD (mg/L)	182	2.0	2.0	2.0
COD (mg/L)	398	12	22	5
TSS (mg/L)	174	3.2	5	3
TKN (mg/L)	33.0	1.9	2.9	1.4
Ammonia-N (mg/L)	24.8	0.21	0.29	0.10
TP (mg/L)	5.0	0.1	0.13	0.06
Fecal coliforms (#/100 mL)	--	2	2	2
NO3-N (mg/L)	--	2.8		

ters is over 90 percent. The effluent meets all permit limits, and is reused for irrigation and lawn watering.

Traverse City, Michigan. The Traverse City Wastewater Treatment Plant (WWTP) went through an upgrade to increase plant capacity and produce a higher-quality effluent, all within the facility's existing plant footprint (Crawford et al. 2005). With the ZeeWeed system, the facility was able to achieve those goals. As of 2006, the plant is the largest-capacity MBR facility in North America. It has a design average annual flow of 7.1 mgd, maximum monthly flow of 8.5 mgd, and peak hourly flow of 17 mgd. The membrane system consists of a 450,000-gallon tank with eight compartments of equal size. Secondary sludge is distributed evenly to the compartments. Blowers for air scouring, as well as permeate and back-pulse pumps, are housed in a nearby building.

Table 3 presents a summary of plant results over a 12-month period. The facility provides excellent removal of BOD, TSS, ammonia-nitrogen, and phosphorus. Figure 6 shows the influent, effluent, and flow data for the year.

Operating data for the Traverse City WWTP were obtained for the same period. The mixed liquor suspended solids over the period January to August averaged 6,400 mg/L, while the mixed liquor volatile suspended solids averaged 4,400 mg/L. The energy use for the air-scouring blow-

ers averaged 1,800 kW-hr/million gallons (MG) treated.

COSTS

Capital Costs

Capital costs for MBR systems historically have tended to be higher than those for conventional systems with comparable throughput because of the initial costs of the membranes. In certain situations, however, including retrofits, MBR systems can have lower or competitive capital costs compared with alternatives because MBRs have lower land requirements and use smaller tanks, which can reduce the costs for concrete. U.S. Filter/Siemens Memcor package plants have installed costs of \$7–\$20/gallon treated.

Fleischer et al. (2005) reported on a cost comparison of technologies for a 12-MGD design in Loudoun County, Virginia. Because of a chemical oxygen demand limit, activated carbon adsorption was included with the MBR system. It was found that the capital cost for MBR plus granular activated carbon at \$12/gallon treated was on the same order of magnitude as alternative processes, including multiple-point alum addition, high lime treatment, and post-secondary membrane filtration.

Operating Costs

Operating costs for MBR systems are typically higher than those for comparable conventional systems. This is because of the higher energy

Table 3.
Summary of Traverse City, Michigan, Performance Results

Parameter	Influent	Effluent		
	Average	Average	Max Month	Min Month
Flow (mgd)	4.3	--	5.1	3.6
BOD (mg/L)	280	< 2	< 2	< 2
TSS (mg/L)	248	< 1	< 1	< 1
Ammonia-N (mg/L)	27.9	< 0.08	< 0.23	< 0.03
TP (mg/L)	6.9	0.7	0.95	0.41
Temperature (deg C)	17.2	--	23.5	11.5

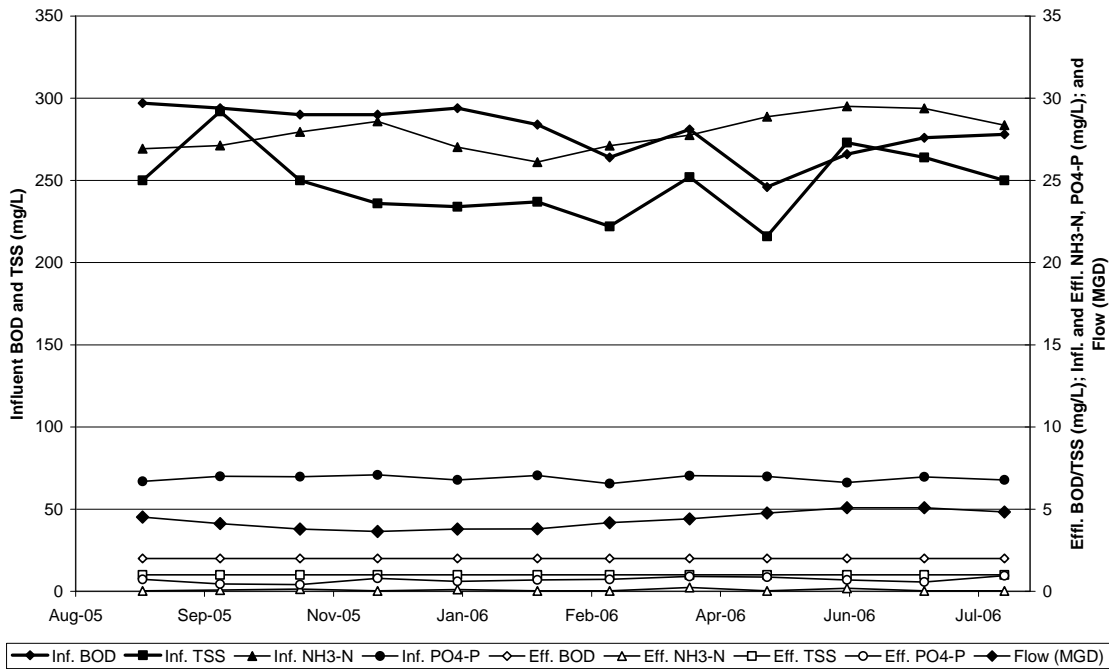


Figure 6. Performance of the Traverse City plant

costs if air scouring is used to reduce membrane fouling. The amount of air needed for the scouring has been reported to be twice that needed to maintain aeration in a conventional activated sludge system (Scott Blair, personal communication, 2006). These higher operating costs are often partially offset by the lower costs for sludge disposal associated with running at longer sludge residence times and with membrane thickening/dewatering of wasted sludge.

Fleischer et al. (2005) compared operating costs. They estimated the operating costs of an MBR system including activated carbon adsorption at \$1.77 per 1,000 gallons treated. These costs were

of the same order of magnitude as those of alternative processes, and they compared favorably to those of processes that are chemical-intensive, such as lime treatment.

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PRODUCT LITERATURE USED

Enviroquip/Kubota. Sales literature.

Siemens. Product literature.

<http://www.usfilter.com/en/Product+Lines/Envirex_Products/Envirex_Products/envirex_mbr_xpress_packaged_plant.htm>.

Zenon. Case studies: Cauley Creek, Georgia.

<http://www.zenon.com/resources/case_studies/water_reuse/CauleyCreek.shtml>.

Zenon. Case studies: Traverse City, Michigan.

<http://www.zenon.com/resources/case_studies/wastewater/TraverseCity.shtml>.

REFERENCES

Crawford, G., G. Daigger, J. Fisher, S. Blair, and R. Lewis. 2005. Parallel Operation of Large Membrane Bioreactors at Traverse City. In *Proceedings of the Water Environment Federation 78th Annual Conference & Exposition*, Washington, DC, CD-ROM, October 29–Nov 2, 2005.

Crawford, G., A. Fernandez, A. Shawwa, and G. Daigger. 2002. Competitive Bidding and Evaluation of Membrane Bioreactor Equipment—Three Large Plant Case Studies. In *Proceedings of the Water Environment Federation 75th Annual Conference & Exposition*, Chicago, IL, CD-ROM, September 28–Oct 2, 2002.

Crawford, G., D. Thompson, J. Lozier, G. Daigger, and E. Fleischer. 2000. Membrane Bioreactors—A Designer's Perspective. In *Proceedings of the Water Environment Federation 73rd Annual Conference & Exposition on Water Quality and Wastewater Treatment*, Anaheim, CA, CD-ROM, October 14-18, 2000.

Fleischer, E.J., T.A. Broderick, G.T. Daigger, A. D. Fonseca, R.D. Holbrook, and S.N. Murthy. 2005. Evaluation of Membrane Bioreactor Process Capabilities to Meet Stringent Effluent Nutrient Discharge Requirements. *Water Environment Research* 77:162–178.

Fleischer, E. J., T. A. Broderick, G. T. Daigger, J. C. Lozier, A. M. Wollmann, and A. D. Fonseca. 2001. Evaluating the Next Generation of Water Reclamation Processes. In *Proceedings of the Water Environment Federation 74th Annual Conference & Exposition*, Atlanta, GA, CD-ROM, October 13–17, 2001.

Hermanowicz, S.W., D. Jenkins, R.P. Merlo, and R.S. Trussell. 2006. *Effects of Biomass Properties on Submerged Membrane Bioreactor (SMBR) Performance and Solids Processing*. Document no. 01-CTS-19UR. Water Environment Federation.

Metcalf & Eddy. 2003. *Wastewater Engineering, Treatment and Reuse*. 4th ed. McGraw-Hill, New York.

Wallis-Lage, C., B. Hemken, et al. 2006. *MBR Plants: Larger and More Complicated*. Presented at the Water Reuse Association's 21st Annual Water Reuse Symposium, Hollywood, CA, September 2006.

