Honolulu Membrane Bioreactor Pilot Study

WateReuse Foundation

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About the WateReuse Foundation

The mission of the WateReuse Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high quality water through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

The Foundation's funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the Southwest Florida Water Management District, and the California Department of Water Resources. Funding is also provided by the Foundation's Subscribers, water and wastewater agencies, and other interested organizations. The Foundation also conducts research in cooperation with the Global Water Research Coalition.

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FOREWORD

The WateReuse Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide high-quality water, protect public health, and improve the environment.

A Research Plan guides the Foundation's research program. Under the plan, a research agenda of high-priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities, including water professionals, academics, and Foundation Subscribers. The Foundation's research focuses on a broad range of water reuse research topics, including the following:

- Definition and addressing of emerging contaminants;
- Public perceptions of the benefits and risks of water reuse;
- Management practices related to indirect potable reuse;
- Groundwater recharge and aquifer storage and recovery;
- Evaluation of methods for managing salinity and desalination; and
- Economics and marketing of water reuse.

The Research Plan outlines the role of the Foundation's Research Advisory Council (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project and provide technical review and oversight. The Foundation's RAC and PACs consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

The Foundation's primary funding partner is the U.S. Bureau of Reclamation (BuRec). Other funding partners include the California State Water Resources Control Board, the Southwest Florida Water Management District, Foundation Subscribers, water and wastewater agencies, and other interested organizations. The Foundation leverages its financial and intellectual capital through these partnerships and funding relationships. The Foundation is also a member of two water research coalitions: the Global Water Research Coalition and the Joint Water Reuse & Desalination Task Force.

This publication is the result of a study sponsored by the Foundation and is intended to communicate the results of this research project. The goal of this project was to introduce and effectively demonstrate MBR technology to engineers, operators, owners, and regulators in Hawaii.

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This project could not have been completed without the insights, efforts, and dedication of many individuals and organizations. These include the members of the research team and Project Advisory Committee (PAC) members (as identified below); the WateReuse Foundation's project managers, Jeff Mosher and then Josh Dickinson; and many key individuals. The consultants involved included Westley Chun of CH2M HILL; Jean Debroux of Kennedy/Jenks Consultants; Greg Arakaki of Kennedy/Jenks Consultants; June Nakamura of Engineering Solutions, Inc.; and Hugh Strom of Aqua Engineers. The Environmental Services personnel included Ross Tanimoto, Eric Takamura, Frank Doyle, Tim Steinberger, and Tim Houghton. The Board of Water Supply personnel included Cliff Jamile, Erwin Kawata, Barry Usagawa, Joe Myers, and Cliff Lum. Special acknowledgments are in order for all of the operations personnel, including Nic Musico, Mark Armas, Bud Reiter, Pat Roberts, Don Henderson, Gary Carolino, Robby Robinson, Bob Choate, Bob Nakamura, and Tod Matsushita. Most of the project work was done by graduate students, including Tieshi Huang, Yingyot Chanthawornsawat, Sumon Kanpirom, Lauren Gannon, Anne Benvel, Jing Hu, Krishna Lamichhane, Yanling Li, Tian Liang, Russel Brain, and Jay Jolly. The MBR vendors and their representatives made large contributions to this project in terms of equipment loans, technical assistance, and various other forms of assistance. Such contributors included Enviroquip (Dennis Livingston, Kim Matheson, Ray Gauthier, Raymond Hoe, Elena Bailey, Jim DeWulf, and Alfonso Garza); Ionics (Michael Sparks and Gene Reahl); Huber (Christian Roedlich and Mike Elhoff); Koch (Alden Whitney, Antonia VanGottenburg, Ben Antrim, and Chinh Hoang); US Filter (Susan Pilgram, Mike Street, Paul Scott, and Ken Windram); and Zenon (Paul Schuler, Mark Murphy, and Deo Phagoo).

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EXECUTIVE SUMMARY

This study consisted of two phases. Phase I consisted of a side-by-side pilot demonstration of six different membrane bioreactor (MBR) systems at the Honouliuli wastewater treatment plant (WWTP) in Ewa Beach, HI. The objective was not to find the optimum performance of any individual MBR system or compare the systems in such a way as to facilitate selection for procurement. The objectives of Phase I were to (i) demonstrate the technology for local engineers, operators, owners, and regulators, (ii) develop operating experience in Hawaii, (iii) promote the technology for adoption in Hawaii, (iv) compare different equipment, and (v) investigate the consistency of water quality, the reliability, and the operability of the technology for three different waste streams. Phase II consisted of a variety of activities, including bench- and pilot-scale tests, aeration testing, and a feasibility study. The objectives of Phase II were (i) pilot testing one MBR at an application site to facilitate the full-scale plant design and acquaint the operations staff with the technology, (ii) pilot testing one MBR at a pump station site to evaluate satellite MBR treatment operation issues, (iii) pilot testing MBR-based thickening and aerobic digestion of secondary sludge to investigate the potential utility of such operations, (iv) conducting a comprehensive MBR feasibility study for the island of Oahu, including satellite reclamation, plant expansions, plant upgrades to facilitate recycling, and decentralized treatment for proposed or new developments, and (v) conducting research on MBR biofouling and aeration mass transfer.

The objectives of the study were achieved. MBR technology was introduced and demonstrated effectively for the numerous local engineers, operators, owners, and regulators who observed the pilot units in operation. Approximately 15 licensed wastewater operators gained hands-on experience with the technology, and many more at least viewed the MBRs in operation. Familiarity with MBRs increased such that they have since been proposed for numerous projects statewide and adopted for a 4-million-gallon-per-day retrofit at Schofield Barracks WWTP on Oahu. The six MBRs compared in this study were of very different configurations in terms of membrane materials, membrane pore sizes, membrane shape, aeration rates, bioreactor configurations, and other parameters. In spite of these differences, there were important similarities as follows: (i) Each of the six pilot MBRs produced very similar, very-high-water-quality permeate with reliability, (ii) permeate water quality was excellent—far superior to conventional activated sludge effluent and to media-filtered tertiary effluent in terms of conventional parameters such as 5-day Biochemical Oxygen demand (BOD_5) (<3 mg/L), total suspended solids (TSS) (<2 mg/L), turbidity (mostly <0.1 NTU), indicator organisms (<1 CFU/100 mL), and UV transmittance (>70%), (iii) MBR permeate is suitable for disinfection with UV radiation since it is compact and does not require a chemical supply train or raise associated handling and storage issues, and (iv) MBRs can operate reliably under variable strength conditions due to extended solid retention time (SRT) in a smaller footprint.

Operation and maintenance observations common to all of the six MBR pilot units are as follows: (i) MBR operations are highly automated and controllable but not maintenance free, (ii) MBRs are easy to operate; however, skilled operators who understand activated sludge, membrane filtration, and automation are needed, (iii) periodic recovery cleaning is necessary (and was required in this study after polymer dumps, power outages, equipment failures, and each phase of testing) but easy and effective (chlorine, 2000 ppm; and hydrochloric acid, 1%), (iv) many more screenings were obtained with a 0.5-mm screen than with a 3-mm screen, (v) the MBRs operated at the flux rates advertised (10 or 15 gal/day-ft^2), and (vi) transmembrane pressure (TMP) was a good indicator of the need to recovery clean the membranes.

Pilot testing of the Zenon MBR at Schofield Barracks facilitated the full-scale plant design and acquainted the operations staff with the technology. The piloting of membrane thickening in a nonstandard mode (using a young sludge) demonstrated the importance of adequate aeration for allowing nitrification or denitrification and preventing biofouling and nitrogen poisoning even if solid reduction goals have been achieved. The MBR feasibility study for Oahu found eight potentially feasible sites for MBRs. Bench studies began to identify biofouling conditions and causes. Pilot aeration testing found that the α factor in oxygen mass transfer was mostly correlated to viscosity (no new relationships were found with other parameters).

This project developed criteria to assist designers and owners in the selection of MBR equipment. Although permeate water quality is essentially the same for all of the six MBRs evaluated, there are differences between the different forms of equipment that can be grouped into cost and noncost factors. Cost issues include membranes and configuration, power and chemical usage, redundancy provisions, pretreatment needs, equipment durability, redundancy, and materials of construction. Noncost factors include ease of operation; control complexity; cleaning frequency, modes, and complexity; and company profiles and experience.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Researchers at the University of Hawaii (UH), Engineering Solutions, Inc. (ESI), and Kennedy/Jenks Consultants (KJ) began this study, titled "Honolulu Membrane Bioreactor Pilot Study" and funded by the WateReuse Foundation (WRF), on December 1, 2004. Some progress was made prior to the initiation of WRF funding. This research study was initiated in April 2003, and side-by-side pilot studies began on September 23, 2003. Research conducted prior to initiation of WRF funding was financed by the Honolulu Board of Water Supply (BWS), the Honolulu Department of Environmental Services—Wastewater (ENV), UH, ESI, KJ, and the Campbell Estate. No distinction is made in this report between results obtained before and after initiation of WRF funding.

Discussions with the City and County of Honolulu (CCH)'s ENV and BWS in 2002 found a series of wastewater treatment applications for which membrane bioreactors (MBRs) may be an ideal technological solution. These include (i) treatment of raw wastewater at pump stations for nearby water recycling applications, (ii) treatment of primary effluent to upgrade existing wastewater treatment plants (WWTPs) for water recycling, (iii) treatment of primary effluent for concurrent nitrogen and phosphorus removal for discharge in environmentally sensitive areas, and (iv) treatment of a high-strength solid-handling recycling stream for organic and color removal. MBRs consist of an activated sludge process in which conventional sedimentation is replaced with micro- or ultrafiltration membranes for solid separation. The resulting effluent, referred to as permeate, is generally of a quality that surpasses that found in conventional activated sludge plus granular medium filtration. In addition, because two unit processes are eliminated (secondary sedimentation and medium filtration) and possibly even a third (primary sedimentation), process footprints are greatly reduced. MBRs also are generally operated at high mixed liquor solid concentrations (8 to 15 g/L) and for long solid retention times (SRTs) (10 to 30 days), resulting in reduced volumes under aeration and high biodegradation efficiency possibly even for recalcitrant and/or emerging contaminants. MBRs generally use permeate pumps to pull a slight vacuum on the membranes that are submerged in the mixed liquor. MBRs employ coarse-bubble aeration for scouring dewatered solids from the membrane surface and consequently require more aeration capacity than does conventional activated sludge.

Because there was no experience with MBRs in Hawaii, an MBR pilot study was conceived in order to demonstrate the technology, verify its utility, and stimulate interest in its application. Research into MBR equipment uncovered multiple vendors and determined that the four leading manufacturers were Zenon, Enviroquip, Ionics, and US Filter. The vendors were approached in late 2002, and local funding was sought through a proposal in January 2003. Some cash funding was obtained (BWS and Campbell Estate), and large, in-kind commitments were made by ENV (headworks facilities, site work, electrical improvements and hookups, lighting, and operations staffing) for a side-by-side pilot study with the four leading MBR vendors. Smaller in-kind commitments were made by UH, ESI, and KJ. Two vendors were willing to send their equipment immediately to Hawaii (Enviroquip and Ionics), and two others were interested but did not have pilot plants immediately available (Zenon and

US Filter). After the study had been under way for several months, a fifth vendor expressed interest and then later joined the study (Huber). After another year, a sixth vendor expressed interest and joined the study (Koch). All vendors delivered their equipment to the site, provided personnel to set up and start up their equipment, and supplied replacement parts as needed at no cost to this project. No monthly rent was charged.

The study consisted of two phases. Phase I was side-by-side pilot study divided into Phase IA (raw wastewater), Phase IB (centrate), and Phase IC (primary effluent). Phase II consisted of a variety of other activities. Two fine screens of different sizes (0.5 and 3 mm) were tested. In this study, it was envisioned that ENV operations staff would operate and maintain the MBR pilots and keep detailed records for three shifts per day. The vendors were asked to have their equipment onsite and running by April 1, 2003. The first MBR pilot unit (Enviroquip) arrived on April 1, 2003, and was operational by April 9, 2003. At that time, the headworks facility was still under construction and would not be completed until May 2003.

1.2 OBJECTIVES

This study consisted of two phases. Phase I consisted of a side-by-side pilot demonstration of five different MBR systems at the Honouliuli WWTP in Ewa Beach, Hawaii. The objective was not to find the optimum performance of any individual MBR system or compare the systems in such a way as to facilitate selection for procurement. The objectives of Phase I were:

- Demonstrate the technology for local engineers, operators, owners, and regulators
- Develop operating experience in Hawaii
- Promote the technology for adoption in Hawaii
- Compare different sets of equipment
- Investigate the consistency of water quality, the reliability, and the operability of the technology for three different waste streams
- In Phase IA, consider raw wastewater as feed
- In Phase IB, consider high-strength centrate waste as feed
- In Phase IC, consider primary effluent as feed

Phase II consisted of a variety of activities, including bench- and pilot-scale tests, aeration testing, and a feasibility study. The objectives of Phase II were:

- Pilot testing one MBR at an application site to facilitate the full-scale plant design and acquaint the operations staff with the technology
- Pilot testing one MBR at a pump station site to evaluate satellite MBR treatment operation issues
- Pilot testing of MBR-based thickening and aerobic digestion of secondary sludge to investigate the potential utility of such operations
- Conducting a comprehensive MBR feasibility study for the island of Oahu, including satellite reclamation, plant expansions, plant upgrades to facilitate recycling, and decentralized treatment for proposed or new developments
- Pursuing the following research topics:
    - Bench-scale MBR biofouling studies
    - Pilot-scale aeration column mass transfer experiments

CHAPTER 2

MATERIALS AND METHODS

2.1 PILOT SITE FACILITY SETUP

The MBR pilot site facility setup included feedwater pumps and piping, a headworks facility with two fine screens, pilot MBRs, and a storage shed. Figure 2.1 shows a schematic of the side-by-side pilot study setup. ENV personnel constructed a headworks facility consisting of an elevated wooden platform to house two different fine screens (0.5- and 3-mm pore sizes) and associated pipework (see Figure 2.2). Submersible pumps at each of three source-water locations and piping to convey water to the headworks were also constructed. A new electrical substation was constructed at the headworks facility, and main breaker boxes and slabs were provided adjacent to five side-by-side MBR pilot equipment sites (see Figure 2.3). New overhead lamp standards were provided at the pilot site as well. A 1000-gal. open-top common feed tank was provided next to the screening platform for the screens to discharge into and the MBRs to draw from. A common effluent (permeate) tank was provided to allow easy viewing during tours and as a site to withdraw hourly samples for compositing (see Figure 2.4). The headworks facility also had water service consisting of in-plant recycled water (tertiary treated, R-1 recycled water) that was used in Phase IB to dilute the high-strength heat-treated centrate feed.

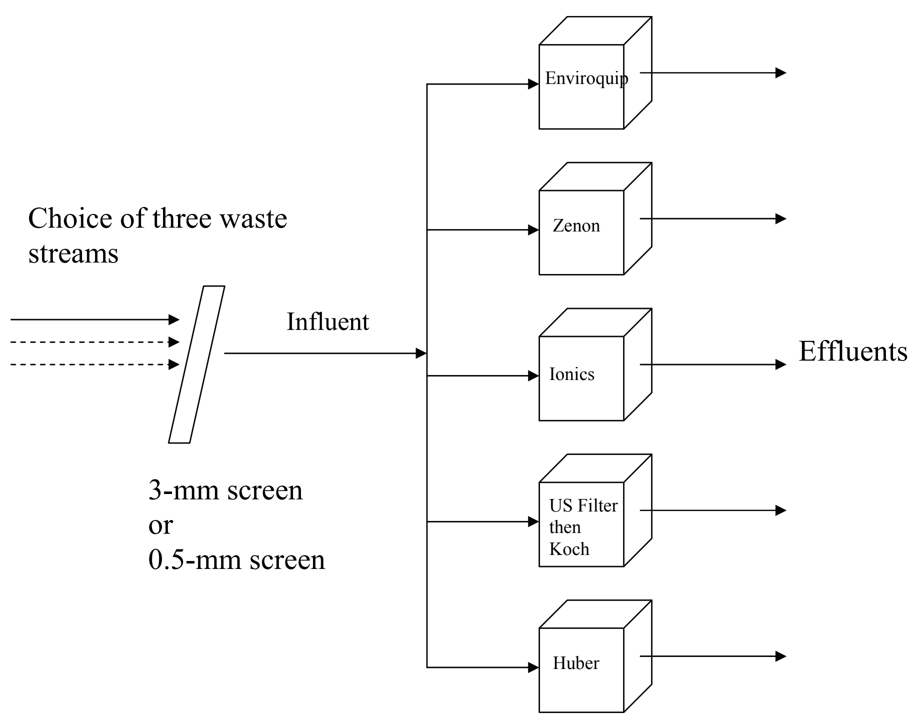

Figure 2.1. Schematic diagram of MBR pilot study setup.

Figure 2.2. Honolulu MBR Pilot Study headworks facility.

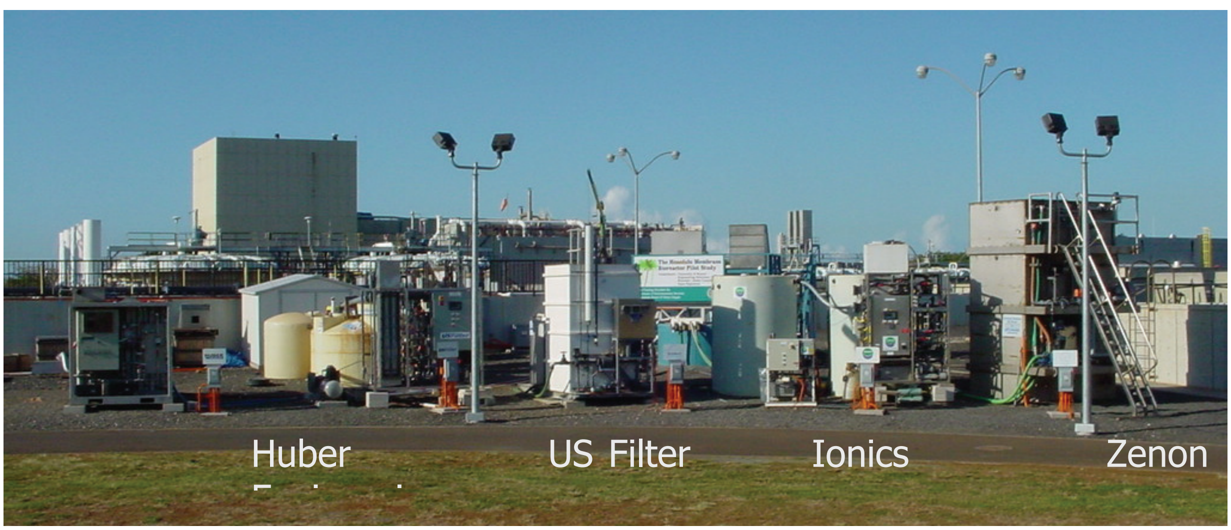

Figure 2.3. Five side-by-side pilot MBRs at the Honouliuli WWTP, Ewa Beach, HI.

Figure 2.4. Honolulu MBR Pilot Study common permeate tank.

In this study it was envisioned that ENV operations staff would operate and maintain the MBR pilot plants and keep detailed records for three shifts per day. The vendors were asked to have their equipment on site and running by April 1, 2003. However, the MBRs did not all arrive at the same time. In addition, not all of the MBRs were operational for the entire study period. Information on pilot equipment arrival dates, initiation of operations, ending operation dates, and feed stream testing periods is presented below. The 0.5-mm-pore-size screen was used only during Phase IA, and thereafter the 3-mm-pore-size screen was used to reduce the volume of screenings and associated operations labor requirements.

The various MBR pilot units arrived in Honolulu on the following dates:

- Enviroquip: April 1, 2003
- Ionics: May 15, 2003
- Zenon: August 20, 2003
- US Filter: March 15, 2004
- Huber: March 16, 2004
- Koch (replaced US Filter): November 15, 2005

The MBR pilot units became operational on the following dates:

- Enviroquip: April 9, 2003
- Ionics: June 3, 2003
- Zenon: September 6, 2003
- Huber: March 30, 2004
- US Filter: April 6, 2004
- Koch (replaced US Filter): December 8, 2005

The test dates for different waste streams were as follows:

- Phase IA: raw wastewater: September 22, 2003, to April 23, 2004
  - 0.5-mm screen
  - Enviroquip, Ionics, Zenon
- Phase IB: heat-treated centrate: April 29, 2004, to July 29, 2004
  - 3-mm screen
  - Enviroquip, Huber, Ionics, US Filter, Zenon
- Phase IC: Primary effluent: August 15, 2004, to January 31, 2005
  - 3-mm screen
  - Enviroquip, Huber, Ionics, US Filter, Zenon
- Primary effluent: February 1, 2005, to February 28, 2005
  - 3-mm screen
  - Enviroquip, Huber, Ionics, US Filter (until November 24, 2004), Zenon (until November 22, 2004)
- Raw wastewater: March 1, 2005, to November 30, 2006
  - 3-mm screen
  - Enviroquip (except from May 4, 2005, to December 12, 2005, when operated as thickener/digester), Huber (until September 2005), Ionics (until September 2005), Koch (beginning December 8, 2005)

It should be noted that operating even one large pilot plant is quite labor intensive and challenging. However, operating up to five different units at the same time for an extended period is extremely challenging. Realistically, it is not recommended to try what we have done here. Pilot plants are not designed for long-term operations, are constructed with less-than-optimal components, and generally have less automation and redundancy than does full-scale equipment. As a consequence, pilot components broke down (four blowers, 10 pumps, two mixers, meters, valves, PLCs, a transformer, and other items). In addition, conditions at the treatment plant such as multiple power outages, polymer dumps, and storm-induced extreme loading events each wrought havoc on the pilot plants. The ENV staff was exceptionally professional and tireless in its efforts to keep the pilots operating. It did an excellent job and cannot be thanked enough.

2.2 PILOT MBRs

MBR pilot systems were provided by six vendors, including Enviroquip, Huber, Ionics, Koch, US Filter, and Zenon. Each MBR system contained patented components and processes, and thus each was different in many important ways. Table 2.1 gives some of the basic characteristics of these six MBRs. Two employed flat sheets, and four used hollow fibers. Four were microfiltration pore size, and two were ultrafiltration pore size. Some of the hollow fibers are supported, but one was not. Some can be located in the aeration basin, and others are placed in a separate cell compartment. The flat sheet systems can be operated on gravity head (without a permeate pump). Table 2.2 gives the pilot MBR membrane surface areas, design flows, and design fluxes ranging from 10 to 17.6 gal/day-ft^2 (GFD). Table 2.3 shows the operating modes employed by the six different pilot MBRs, including type of air scour, permeation relax, and backpulse. Table 2.4 shows design criteria for the five different MBRs, including maximum month flux, peak hour flux, range of transmembrane pressures (TMPs), and aeration and prescreening requirements.

Table 2.1. General characteristics of six pilot MBR systems

Vendor	Membrane configuration	Membrane location	Membrane type	Pore size (μm)
Enviroquip (Kubota)	Vertical flat panel	Aeration basin	Microfiltration	0.4
Huber	Rotating flat panel	Aeration basin	Ultrafiltration	0.02
Ionics (Mitsubishi)	Horizontal hollow fiber (Steripore)	Aeration basin	Microfiltration	0.4
Koch	Vertical hollow fiber	Cell compartment	Microfiltration	0.1
US Filter (Memtec)	Vertical hollow fiber	Cell compartment	Microfiltration	0.08
Zenon	Vertical hollow fiber (ZeeWeed 550d)	Cell compartment	Ultrafiltration	0.04

Table 2.2. Pilot MBR membrane surface areas and flow rates

Vendor	Membrane area (ft^2)	Pilot flow rate (gpm)	Pilot flow rate (gal/day)	Pilot flux (GFD)
Enviroquip (Kubota)	630	6.5	9375	14.7
Huber	775	9.5	13,680	17.6
Ionics (Mitsubishi)	1130	7.9	11,375	10
Koch	323	2.7	3888	14.3
US Filter (Memtec)	575	4.0	5760	10
Zenon	460	3.2	4600	10

Table 2.3. Pilot MBR operating modes

Vendor	Operating mode
Enviroquip (Kubota)	Continuous air scour and permeation relax
Huber	Continuous air scour on one side and intermittent water scour[a]
Ionics (Mitsubishi)	Continuous air scour and permeation relax
Koch	Cyclic air scour (33% time on) and intermittent backpulse (10 s/5 min)
US Filter (Memtec)	Continuous air scour, permeation relax, and intermittent backpulse (30 s/12 min)[a]
Zenon	Cyclic air scour (50% time on), permeation relax, and intermittent backpulse (15 s/15 min)[a]

[a]These features provided on existing units but phased out of new designs.

Table 2.4. Design criteria for six different pilot MBRs

Vendor	Design flux (GFD)	Peak flux (GFD)	TMP (−psi)	Air use (CFM/100 ft^2)	Screen (mm)
Enviroquip (Kubota)	14.7	43	0.1–4	3.0 1.8 for > 4 MGD[a]	3
Huber	13–14	33.5	2–6	1.4–1.8	3
Ionics (Mitsubishi)	10	32.3	1–4	1.8	1–2
Koch	14.3	26.8	0.2–2	1.0	3
US Filter (Memtec)	15	30	1–4	1.6	2
Zenon	10–15	22	2–8	1.7–1.8	1–2

[a]MGD, millions of gallons per day.

Figure 2.2 (above) shows the pilot test site when five of the MBRs were operated side by side (Enviroquip, Huber, Ionics, US Filter, and Zenon). Later, the Zenon unit was moved to the Schofield Barracks WWTP (SBWWTP) for operator training and water quality data were obtained (see Figure 2.5). A different containerized Zenon MBR was briefly operated at a remote pump station in Wahiawa to demonstrate this application, and water quality data were also obtained (see Figure 2.6). Eventually, the Koch pilot MBR replaced the US Filter MBR (see Figure 2.7)

Figure 2.5. Zenon pilot MBR at SBWWTP, HI.

Figure 2.6. Containerized Zenon pilot MBR at a pump station in Wahiawa, HI.

2.3 PILOT-SCALE MEMBRANE THICKENER/DIGESTER

The Enviroquip pilot MBR unit was retrofitted and converted into a PAD-K thickener/digester by Enviroquip staff, and operations commenced on May 4, 2005. Modifications were made to the anoxic tank (removal of propeller mixer and addition of aerobic digester sparger) and the permeate pump. An automatic feed system, including a pump, floats, and 1500 ft of piping to supply secondary sludge (from Honouliuli WWTP's trickling filter/solid-contact [TF/SC] process), was constructed by UH personnel. For thickening, the membranes were operated at only 5 GFD (1/3 of the MBR rate), at double the aeration rate of MBR, and at a normal relax cycle time of 9 min of permeation and 1 min of relax. Figure 2.8 shows the operator interface in PAD-K mode.

Figure 2.7. Koch pilot MBR at Honouliuli pilot test site, Ewa Beach, HI.

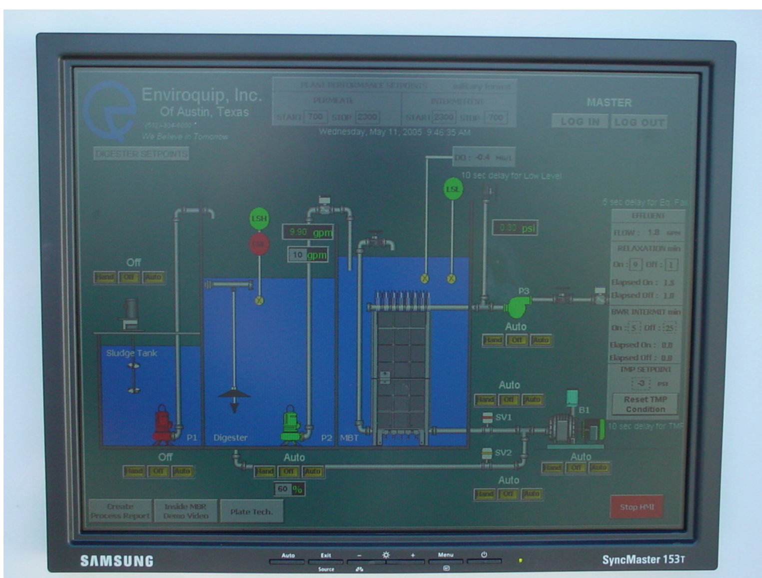

Figure 2.8. Enviroquip pilot MBR operator interface in PAD-K mode.

2.4 BENCH-SCALE MBR SETUP

Bench-scale Enviroquip and Ionics MBR systems were constructed (see Figure 2.9). These were initially operated in the Environmental Engineering Lab at the UH (December 5, 2005, to January 6, 2006). Due to difficulties in obtaining and maintaining fresh wastewater at the lab, the bench MBRs were moved to Honouliuli WWTP and reseeded on January 16, 2006.

The bench-scale reactors (one flat-plate type and one hollow-fiber type) were operated via programmable logic controllers for feed, mixed-liquor recycling, anoxic mixing, and permeation. A SCADA system was utilized for monitoring of permeate flow rate and TMP. pH controllers were employed to maintain the pH at near 7.0. Screened (3-mm pore size) raw wastewater (from the Honouliuli WWTP pilot test facility) was used as feed.

Figure 2.9. Bench-scale Enviroquip (right) and Ionics (left) MBRs at Honouliuli WWTP.

2.5 PILOT-SCALE AERATION COLUMN

A pilot aeration column (30-in. diameter, 20-ft height) was constructed at the Honouliuli WWTP (Figure 2.10) by using an HDPE storm sewer pipe. An off-gas analyzer was constructed (to measure oxygen transfer efficiency [OTE] under steady-state conditions) that includes a fuel cell gaseous oxygen analyzer and carbon dioxide–water vapor sorption columns. Three different 8-in.-diameter fine-pore diffusers (ceramic, membrane, and plastic types) were utilized for clean water and process water (sludge) aeration tests.

Figure 2.10. Pilot aeration column at MBR pilot test site, Ewa Beach, HI.

2.6 SAMPLING AND ANALYTICAL PROTOCOLS

Routine operation and maintenance of the MBR pilot units were performed by certified wastewater operations personnel employed by ENV. Personnel assigned to the secondary process area at the treatment plant were responsible for checking the status of the MBRs on each shift. In addition, the day shift operator collected mixed liquor samples for laboratory analysis of suspended solids, completed the analyses, calculated required sludge waste volumes, and performed sludge wasting as needed. These suspended-solid data were used for operations only.

Graduate students from UH performed sampling and analysis activities 5 days per week. The graduate students maintained all of the sampling equipment, which included cleaning sample buckets and transfer tubing and programming the samplers. The graduate students also conducted all of the chemical analyses described in this report. Two types of samples were collected from the operating MBR treatment units; 24-h composite samples, and instantaneous grab samples. Composite samples were obtained by using programmable sampling devices (by ISCO) that collect 0.25 L of sample every hour of the day. The samples were mixed together in a single bottle inside the samplers, which were kept on ice at all times. Grab samples were obtained by dipping the appropriate sample container(s) into access ports in the MBR pilot units. Samples were routinely collected from 11 locations designated as follows:

- Influent common to all units (INF)
- Effluent from each unit (EFF1, EFF2, EFF3, EFF4, and EFF5)
- Aeration tank of each unit (AIR1, AIR2, AIR3, AIR4, and AIR5)

The sampling and analysis schedule is shown in Table 2.5. Grab samples of INF and EFFx were collected 5 days per week and were analyzed for fecal coliform (FC) and coliphage (CP). The turbidity (NTU) and UV transmittance at 254 nm (UVT_{254}) of all grab samples were also measured. Composite samples of INF, EFFx, and AIRx (AIR1, AIR2, AIR3, AIR4, AIR5) were taken 5 days per week. All of these samples were analyzed for biochemical oxygen demand (BOD_5), total suspended solids (TSS), and color. In addition, 3 days per week, these samples were analyzed for chemical oxygen demand (COD), NTU, and UVT_{254}, total Kjeldahl nitrogen (TKN), ammonia-N (NH_4) nitrate/nitrite (NO_3), phosphate ion (PO_4), total phosphorus (TP), total organic carbon (TOC), and total dissolved solids (TDS). In addition, once per week, the composite samples were analyzed for oil and grease (O&G), anions (F, Cl, NO_2, NO_3, Br, PO_4, and SO_4), and cations (Li, Na, NH_4, K, Ca, and Mg). The dissolved oxygen (DO) and pH measurements were made in the tankage while in service (in situ) rather than upon removed samples. To make the in situ measurements, devices (probes) were lowered into the tanks. All sampling, preservation, hold times, and analytical measurements were conducted or made according to procedures detailed in the 20th edition of *Standard Methods for the Examination of Water and Wastewater* (APHA, 1998). The specific methods utilized are shown in Table 2.6. Soluble microbial products (SMP) and extracellular polymeric substance (EPS) carbohydrate and protein fractions were measured as follows: cation exchange resin extraction (Frolund et al, 1996), carbohydrates (Lowry et al., 1951), and proteins (Dubois et al., 1956). The sampling schedule for the bench-scale MBRs is shown in Table 2.7.

Table 2.5. Pilot MBR sampling and analysis schedule

	Grab samples		24-h composite samples	
Location	**Frequency (duration)**	**Parameters analyzed**	**Frequency (duration)**	**Parameters analyzed**
INF EFF1 EFF2 EFF3 EFF4 EFF5	5 days per week	FC CP NTU UVT_{254}	5 days per week 3 days per week 1 day per week	BOD_5 TSS Color TOC, TKN, NO_3 COD, TP, PO_4 TDS, NTU, UVT_{254} Anions/cations O&G
AIR1 AIR2 AIR3 AIR4 AIR5	5 days per week	TSS VSS[a] PH (in situ) DO (in situ)		

[a]VSS, volatile suspended solids.

Table 2.6. Pilot MBR analytical methods

Analyte	Method
BOD_5	Method 5210 B
TOC	Method 5310 B
COD	Method 5220 D
O&G	Method 5520 B
TSS	Method 2540 D
VSS	Method 2540 E
TKN	Method 4500-N_{org} C
NO_3	Method 4500-NO3 E
NH_4	Method 4500-NH3 D
TP	Method 4500-P E
PO_4	Method 4500-P E
TDS	Method 2540 C
NTU	Method 2130 B
UVT_{254}	Method 5910 B
DO	Method 4500-O G
pH	Method 4500-H B
Color	Hach method 8025
Alkalinity	Method 2320 B
Anions/cations	Ion chromatography
Fecal coliform	Method 9222 E
Coliphage	Method 9224 C and F (male-specific RNA coliphage using *Escherichia coli* F_{amp} host)

Table 2.7. Bench-scale MBR sampling and analysis schedule

Parameter	Location	Sampling days
COD	In, out	M, Tu, W, Th, F
BOD, TOC	In, out	M, W, F
TSS, VSS	ML	M, Tu, W, Th, F
TSS, VSS	In, out	M, W, F
TDS	In, out	W
pH	In, out	M, Tu, W, Th, F
NH_3-N, total-N	In, out	M, W, F
Total-P	In, out	M, W, F
Anions	In, out	W
Conductivity	In, out	M, Tu, W, R, F
Turbidity	Out	M, Tu, W, R, F
Temperature, DO	ML	M, Tu, W, R, F
TMP	Permeate line	Continuous
Alkalinity	In, out	M, W, F
Color, UVT_{254}	Out	W
O&G	In, out	Biweekly
Fecal coliform	In, out	W
Silt density index	Out	W
PSD[a]	ML	M, W, F
Protein and carbohydrate EPS	ML	M, W, F
Protein and carbohydrate SMP	ML, out	M, W, F
Viscosity	ML	M, W, F
Microbial diversity	ML, biofilm	W
Critical flux	ML	Every Sa

[a]PSD, particle size distribution.

CHAPTER 3

RESULTS AND DISCUSSION: PHASE I—SIDE-BY-SIDE OPERATION OF PILOT MBRs

3.1 OPERATING CONDITIONS

Phase I had three parts. In Phase IA, raw wastewater was treated. In Phase IB, high-strength centrate was treated. In Phase IC, primary effluent was treated. The goal of Phase I was to demonstrate the utility of the MBR technology for treatment of wastewater and to provide a comparison of different MBRs in terms of performance and operational issues, including water quality and removal efficiencies, equipment configuration and degree of complexity, ease of operation, and maintenance requirements. The main water quality goals were to reduce BOD and TSS to less than 5 mg/L, have turbidity less than 0.2 NTU, have UVT greater than 65%, and have <1 fecal coliform CFU/100 mL. There were no nutrient removal goals, and no attempt was made to optimize pilot MBR operations for nutrient removal. Each pilot MBR was operated at vendor-recommended conditions of flux, and no attempts were made to provide a competition to determine a ranking of the individual membranes or MBR systems in terms of membrane life, durability, cost-effectiveness, or other metric. Conducting a completely fair and valid evaluation of that type with pilot equipment is not thought to be possible anyway. Instead, extensive water quality data were collected, and observations of “operability” were made.

3.2 PERFORMANCE—WATER QUALITY

3.2.1 Raw Wastewater Feed

The goal of Phase IA was to demonstrate the utility of the MBR technology for treatment of raw wastewater. Phase IA took place from September 22, 2003, to April 23, 2004 (7 months). The pilot MBRs were operated nearly continuously during this period, except for short shutdowns (1 or 2 days) caused by power failures, equipment failures, needed cleanings, and a single extended shutdown (December 10, 2003, until January 13, 2004) due to heavy rains at the Honouliuli WWTP (100-year storm flooding and major process equipment failures). We sought to test all five MBR side by side; however, only three (Enviroquip, Ionics, and Zenon) were available for this portion of the study. The Huber and US Filter MBRs arrived just in time to begin Phase IB (centrate), and the Koch unit arrived after completion of Phase IC (primary effluent). The Huber and Koch MBRs were operated on raw wastewater feed long after Phase IA was completed; however, these data are presented in this section. The US Filter MBR was never operated on raw wastewater. A 0.5-mm-pore-size fine screen was used for pretreatment of raw wastewater (2-in. coarse screened only) in this phase. The CCH was interested in the treatment of raw wastewater for applications such as treatment plant expansion, treatment plant upgrades for water recycling or nutrient removal, and satellite water recycling. The main water quality goals were to reduce BOD and TSS to less than 5 mg/L, keep turbidity to less than 0.2 NTU, have a UVT greater than 65%, and to have <1 fecal coliform CFU/100 mL. There were no nutrient removal goals, and no attempt was made to optimize pilot MBR operations for nutrient removal. The data are divided into process operating data and water quality data. The process operating data include flux, TMP, mixed liquor suspended-solid concentrations (MLSSs), and DO concentrations. The water quality data include influent and effluent BOD_5, TOC, TSS, total-N, ammonia-N, nitrate-N, total-P, orthophosphorus, color, turbidity, UVT_{254}, alkalinity, O&G, TDS, fecal coliform, and fecal coliphage. COD was not measured during Phase IA.

3.2.1.1 Process Operating Data

The MBRs were operated at their design fluxes during Phase IA (Enviroquip, 14.7 GFD; Ionics and Zenon, 10 GFD). The TMPs of each unit were monitored and were a good indicator of needed cleaning (generally when TMP > −4 psi). Each of the MBR pilots was cleaned in place several times by using either a dilute chlorine solution or a dilute acid solution if the chlorine cleaning was inadequate. Cleanings would normally be required only annually or semiannually. However, during this pilot test, there were initially several incidents in which polymer from the main treatment plant was allowed to contaminate the MBRs. Practices were modified to alleviate this problem. Also, during Phase IA, there were several sustained power outages and several large storms that caused shutdowns and/or greatly fluctuating influent conditions necessitating membrane cleanings. MBRs are generally operated by maintaining a target MLSS rather than a target SRT. The MBR pilot units were operated at an MLSS between 6000 and 16,000 mg/L in Phase IA (see Figures 3.1 and 3.3). Several large storms and associated equipment failures at the Honouliuli WWTP during this phase caused very high levels of influent solids (Figure 3.2) that greatly increased impacted MLSSs. It was found that the operation was optimal between 10,000 and 12,000 mg/L for these pilot MBR units. The Ionics pilot unit was unable to effectively build an MLSS initially due to the lack of a mixer in its anoxic tank. After a mixer was installed, the unit was able to rapidly build solids. It was observed that when the MLSS was very high, the pilot units were dissolved, oxygen was limited, and nitrification was inhibited (see Figure 3.4).

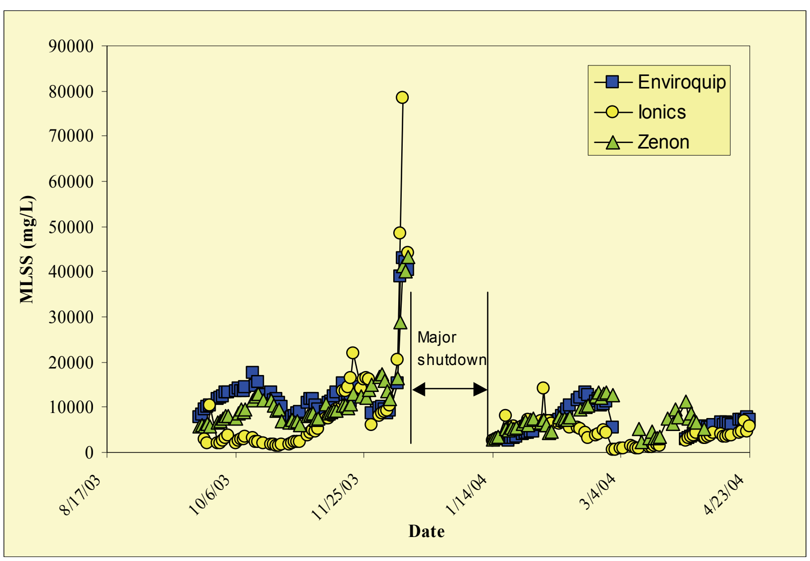

Figure 3.1. MLSSs during Phase IA (raw wastewater).

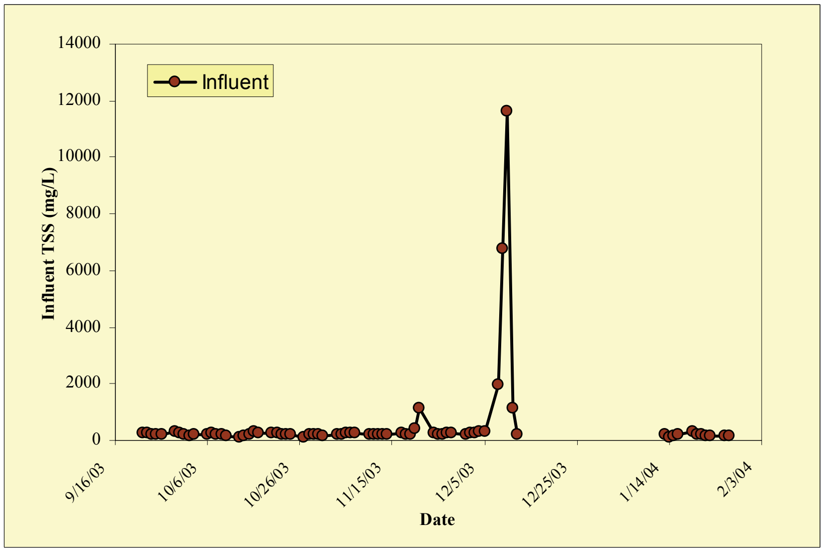

Figure 3.2. Influent suspended solids during Phase IA (raw wastewater).

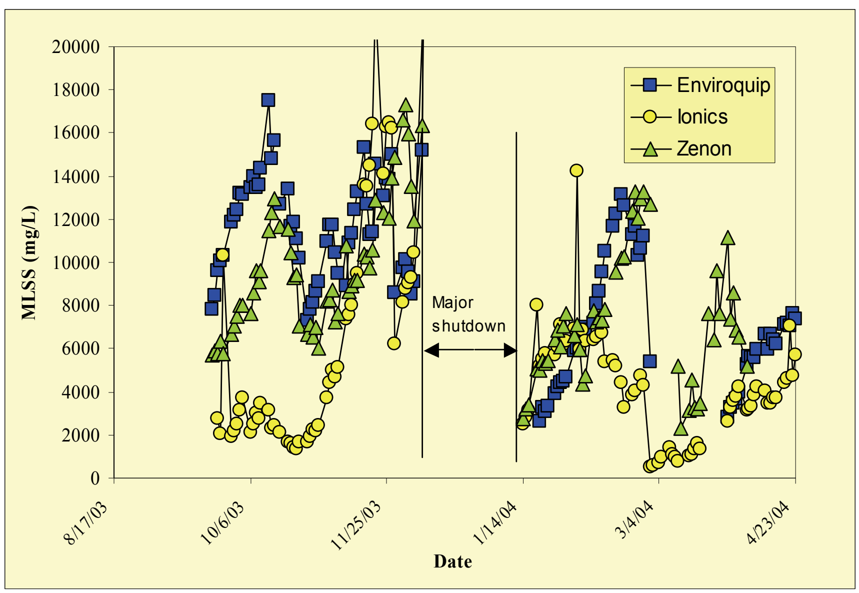

Figure 3.3. MLSSs during Phase IA (excluding peaks).

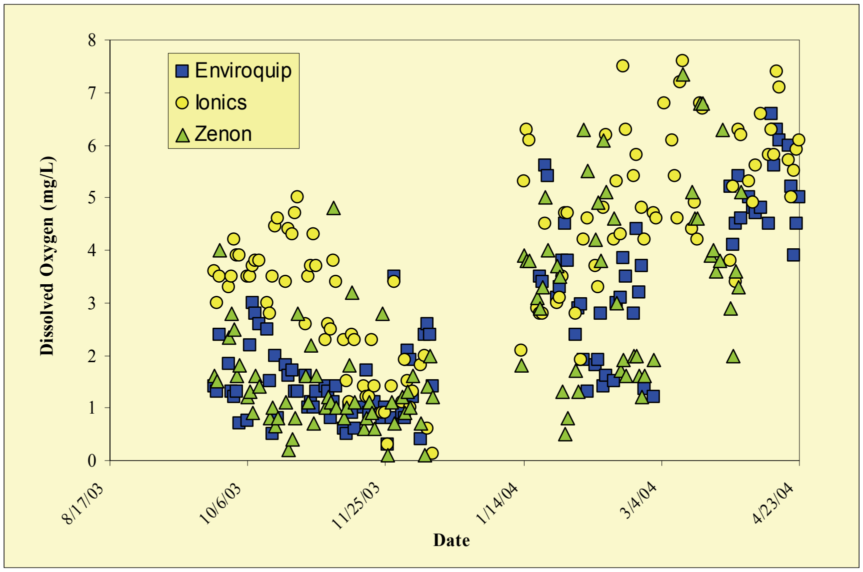

Figure 3.4. Mixed liquor DO during Phase IA (raw wastewater).

3.2.1.2 Water Quality Data

The water quality data are presented in Figures 3.5 through 3.29 and Tables 3.1 through 3.3. The data associated with the two large storms (November and December 2003) have been removed from these figures and tables. The data associated with these events are discussed separately at the end of this section under the heading of "Stress testing." Overall, the effluent (permeate) water quality produced by each of the MBRs was excellent by industry standards for secondary effluent and/or filtered secondary (tertiary) effluent. Many of the parameters were analyzed 5 days per week during Phase IA, resulting in approximately 150 data points each. Therefore, most of the data are presented in the form of distributions rather than time-course plots. In this case, the data sets are analyzed to determine the percentage of the data points that are smaller than a given numerical value. This arrangement allows the reader to easily see the overall distribution of the data as well as to get a feel for the maximum, minimum, and average values. Overall, average influent and effluent values and overall removal efficiencies for all of the water quality parameters analyzed are reported at the end of this section.

BOD. Influent and effluent BOD_5 data are shown in Figures 3.5 and 3.6, respectively. The data indicate that the raw wastewater feed was of medium strength and that the BOD_5 varied between approximately 125 and 425 mg/L. In addition, approximately 80% of the data fall between 200 and 350 mg/L. Figure 2.6 shows the very low values of effluent BOD_5 that are typical for MBR systems. The figure indicates that more than 90% of the BOD_5 values are < 5 mg/L for each of the MBRs and that the performances of the three different types of MBRs are very comparable. Many of the MBR vendors will guarantee permeate BOD averages of less than 5 mg/L, which is borne out in this data set. In fact, the average values were actually all less than 2 mg/L.

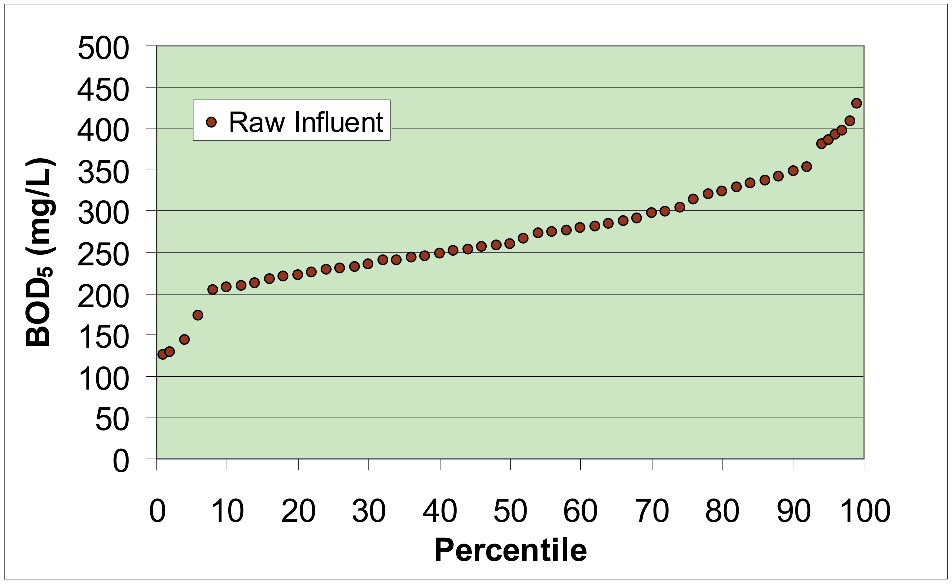

Figure 3.5. Raw influent BOD_5 distribution during Phase IA.

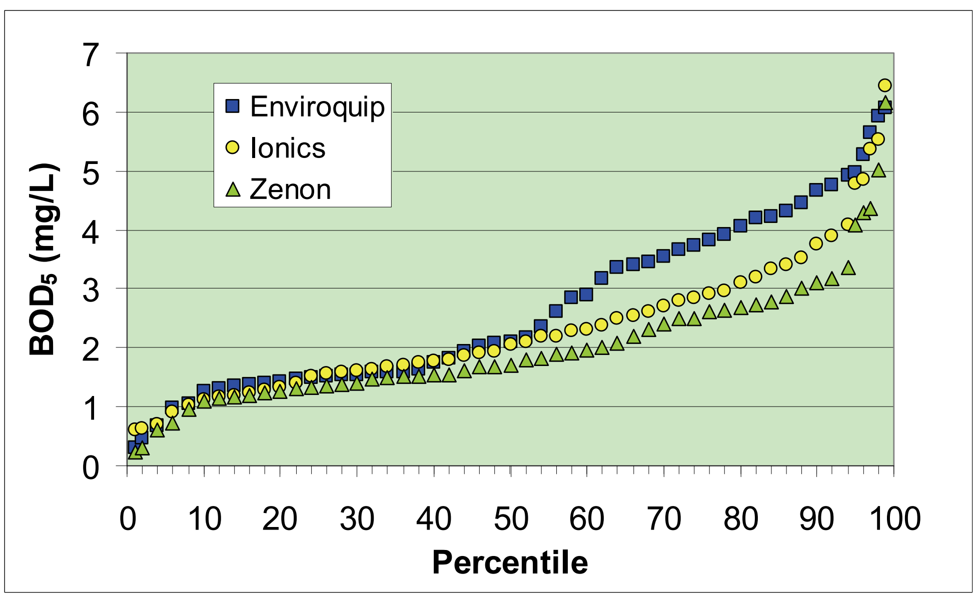

Figure 3.6. Effluent (permeate) BOD_5 distributions during Phase IA (raw wastewater).

TOC. Influent and effluent TOC data are shown in Figures 3.7 and 3.8, respectively. The data indicate that the TOC varied between approximately 20 and 140 mg/L. Figure 3.8 shows that the MBR permeates contain small yet significant amounts of organic carbon. Comparison of Figures 3.5 and 3.7 indicates that influent BOD_5 is approximately 400 to 500% larger than influent TOC, while comparison of Figures 3.6 and 3.8 indicates that effluent TOC is larger than effluent BOD_5. This means that a small amount of soluble organic matter that is not readily degradable as BOD_5 passes through the MBR systems. This amount is often denoted as SMP, which can be fractionated into carbohydrates, proteins, and lipids. Figure 3.8 seems to show some differences between the MBRs, with somewhat higher concentrations of TOC passing through the Enviroquip unit (about 30% of values are greater than 12 mg/L versus less than 10% greater than 12 mg/L for Ionics and Zenon).

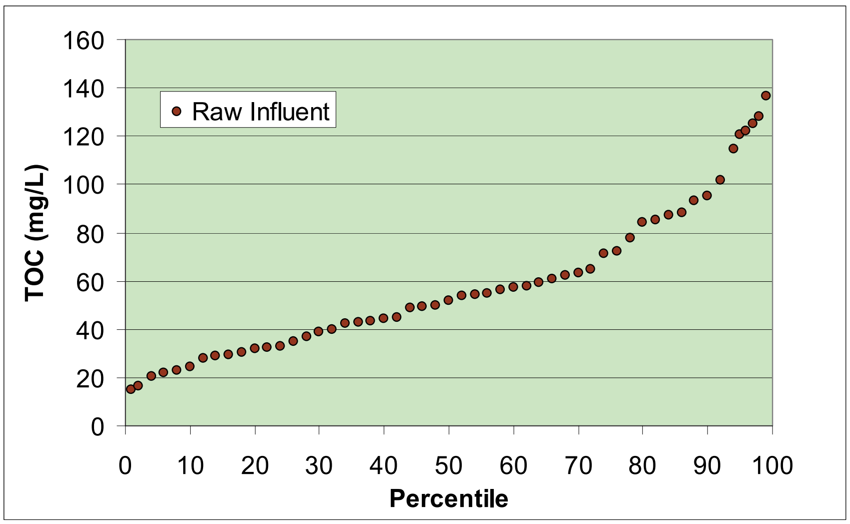

Figure 3.7. Raw influent TOC concentration distributions during Phase IA.

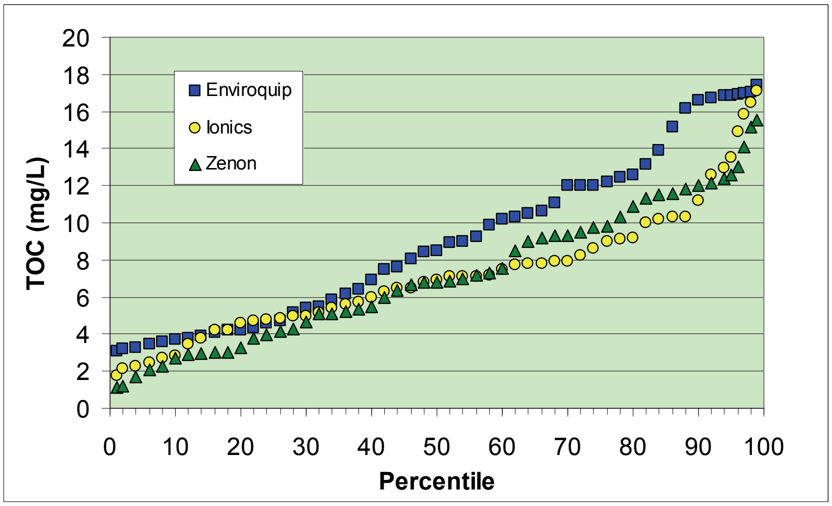

Figure 3.8. Effluent (permeate) TOC distributions during Phase IA (raw wastewater).

TSS. Influent and effluent TSS data are shown in Figures 3.9 and 3.10, respectively. The data indicate that the raw wastewater feed was of medium strength and that the TSS varied between approximately 125 and 400 mg/L. In addition, approximately 80% of the data fall between 175 and 300 mg/L. Figure 3.10 shows the very low values of effluent TSS that are typical for MBR systems. The figure indicates that more than 90% of the TSS values are less than 3 mg/L for each of the MBRs and that the performances of the three different types of MBRs are very comparable. Many of the MBR vendors will guarantee permeate TSS averages of less than 5 mg/L, which is borne out in this data set. In fact, the average values were actually all close to 1 mg/L.

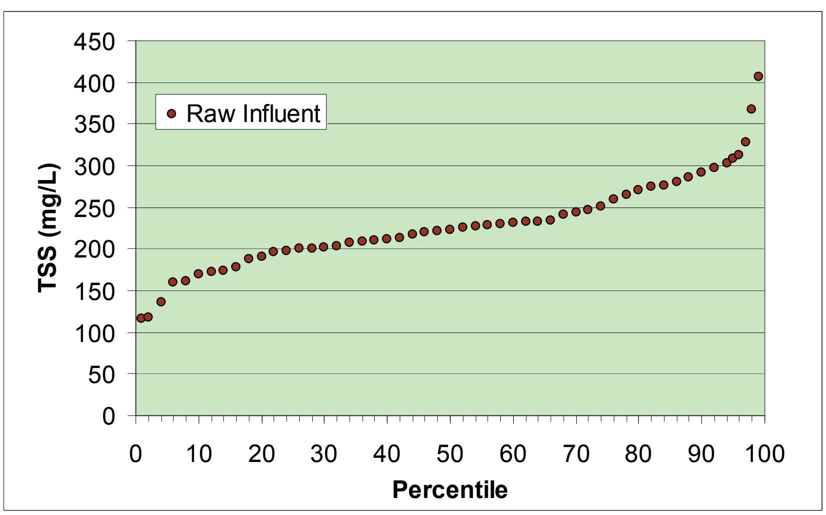

Figure 3.9. Raw influent TSS concentration distributions during Phase IA.

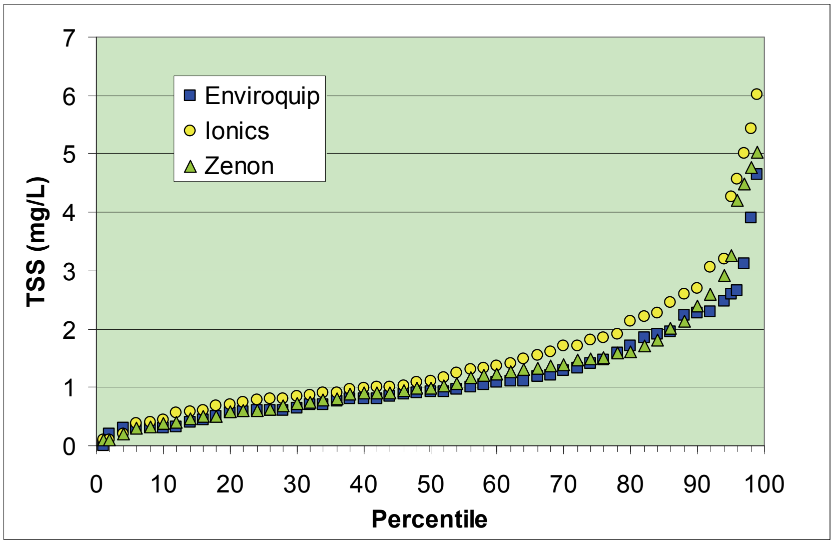

Figure 3.10. Effluent (permeate) TSS distributions during Phase IA (raw wastewater).

Nitrogen species. Influent, effluent, and removal efficiency data for total nitrogen are shown in Figures 3.11, 3.12, and 3.13, respectively. And influent ammonia, effluent ammonia, and effluent nitrate data are shown in Figures 3.14, 3.15, and 3.16, respectively. The data indicate that the raw wastewater feed was of medium strength and that the total nitrogen varied between approximately 25 and 60 mg/L. In addition, approximately 75% of the data fall between 30 and 50 mg/L. Ammonia nitrogen varied from 15 to 45 mg/L. Figure 3.12 indicates that the amount of total nitrogen remaining in the effluent varied from nearly zero to almost 40 mg/L. Because all three of the MBR pilots used in Phase IA are equipped with anoxic zones and mixed liquor recycling systems, these units are capable of significant nitrogen removal. However, the degree of nitrogen removal is dependent upon achievement of nitrification prior to denitrification. At various times there was insufficient DO present in the MBRs (due to high TSS concentrations) to allow complete nitrification, and under these conditions, denitrification-based nitrogen removal was reduced. This can be observed in Figures 3.15 and 3.16, which show that complete nitrification was achieved between 50 and 75% of the time during Phase IA in the different MBRs.

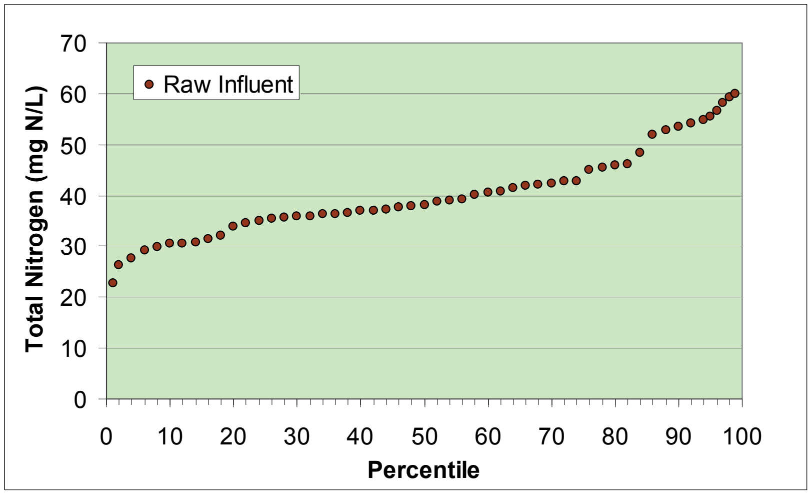

Figure 3.11. Raw influent total nitrogen concentration distributions during Phase IA.

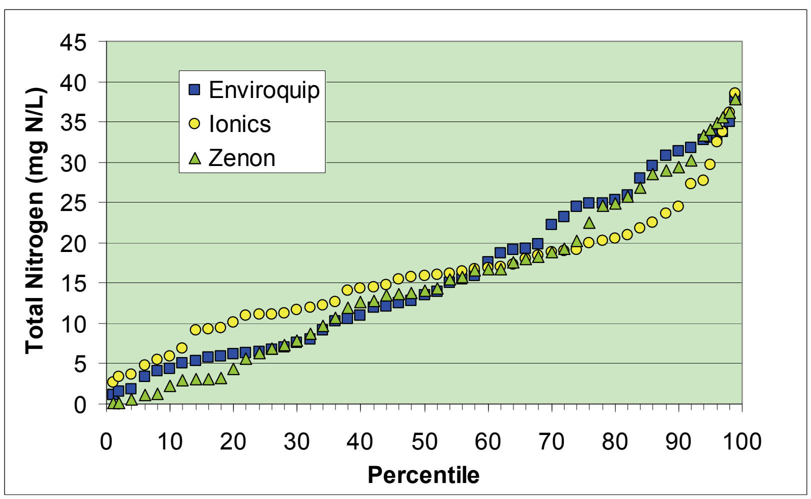

Figure 3.12. Effluent (permeate) total nitrogen distributions during Phase IA (raw wastewater).

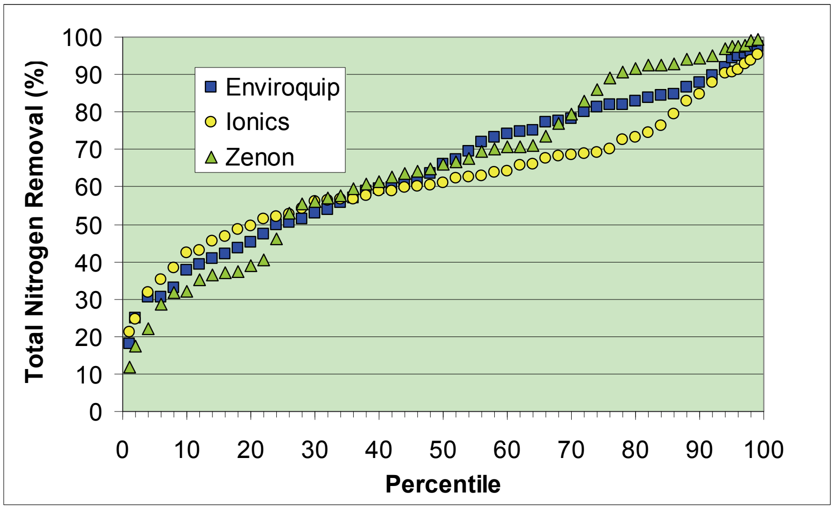

Figure 3.13. Total nitrogen removal efficiency distributions during Phase IA (raw wastewater).

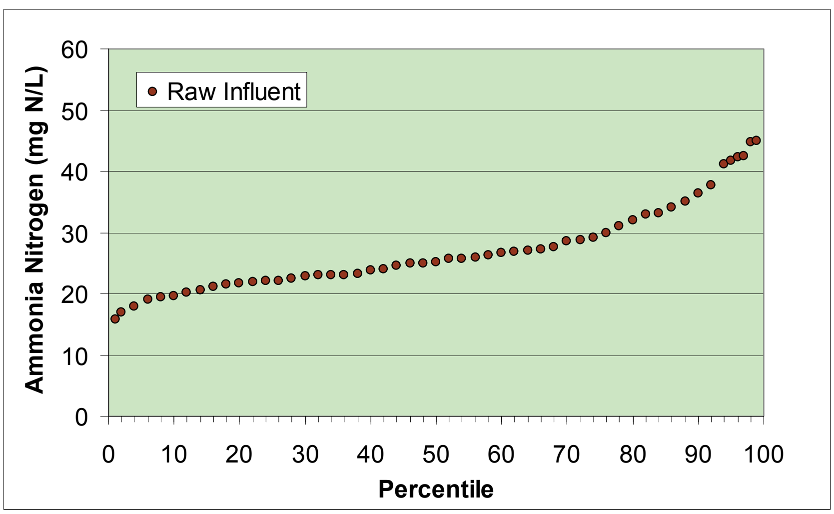

Figure 3.14. Raw influent ammonia nitrogen distributions during Phase IA (raw wastewater).

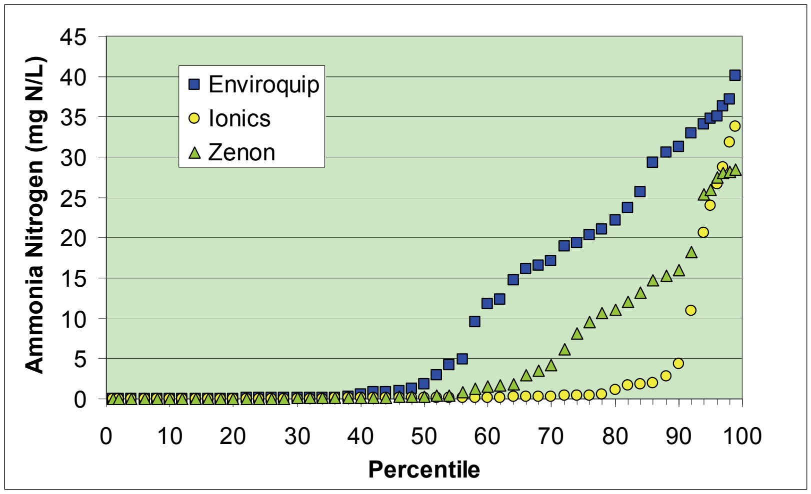

Figure 3.15. Effluent (permeate) ammonia nitrogen distributions during Phase IA (raw wastewater).

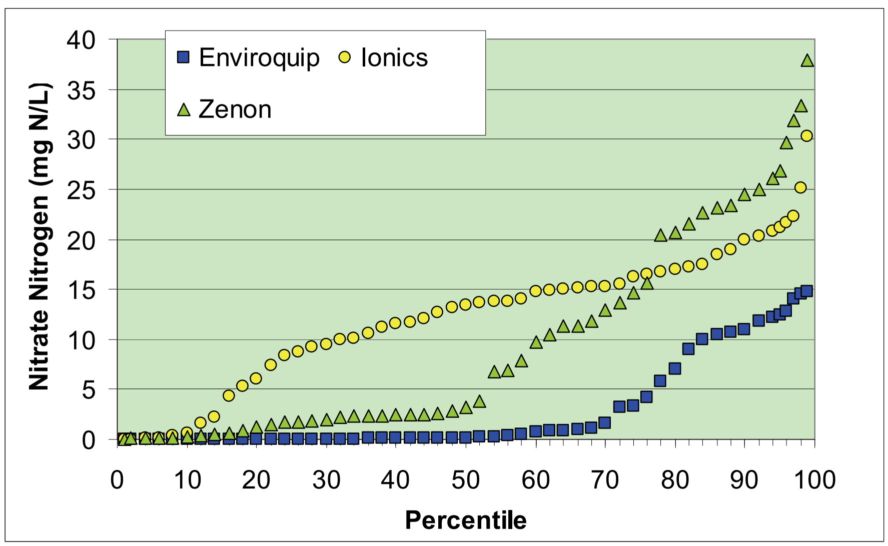

Figure 3.16. Effluent (permeate) nitrate nitrogen concentration distributions during Phase IA (raw wastewater).

Phosphorus species. Influent, effluent, and removal efficiency data for total phosphorus are shown in Figures 3.17, 3.18, and 3.19, respectively. The data indicate that the raw wastewater feed contained between approximately 3 and 15 mg of total phosphorus/L. Figure 3.18 shows that effluent total phosphorus varied from nearly zero to about 6 mg/L. Figure 3.19 indicates that phosphorus removal was significant for each of the MBRs and that differences occurred. Specifically, the Ionics unit seemed to remove somewhat less phosphorus than did the other MBRs. None of these MBR pilots was specifically set up for biological phosphorus (Bio-P) removal or coagulant addition for chemical P removal. Therefore, the observed P removal can be attributed to normal biological uptake. Figure 3.20 indicates that there were slight differences in the amount of orthophosphate in the MBR permeates.

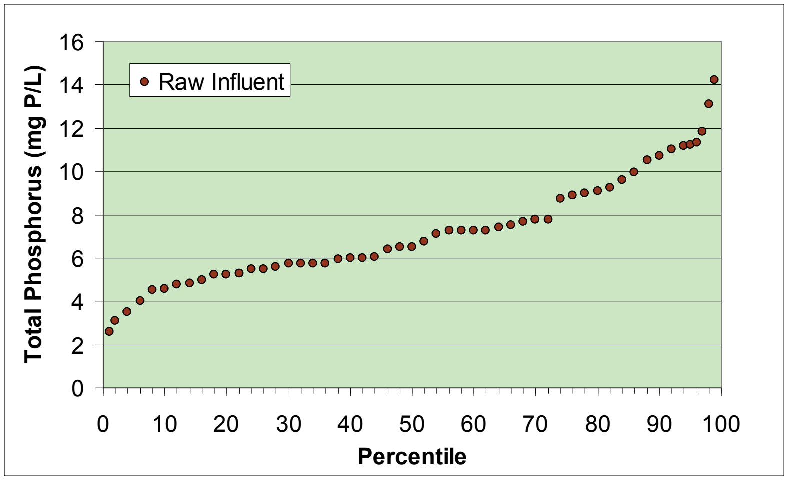

Figure 3.17. Raw influent total phosphorus concentration distributions during Phase IA.

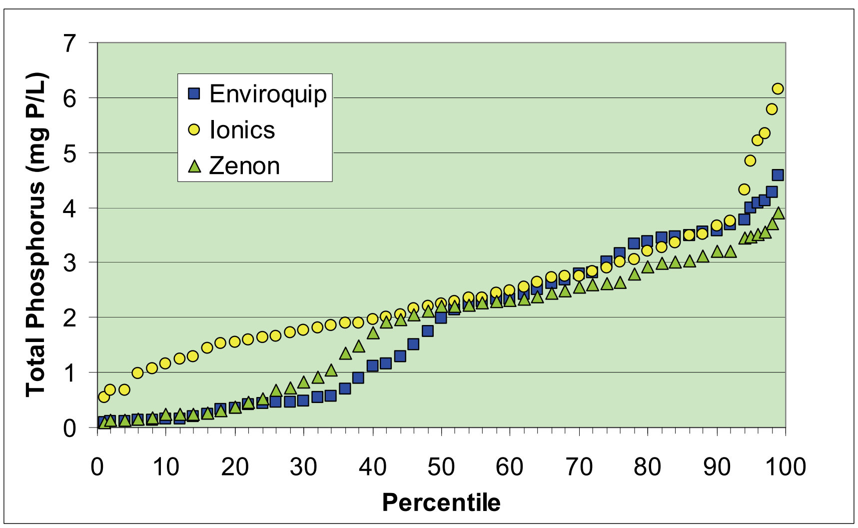

Figure 3.18. Effluent (permeate) total phosphorus concentration distributions during Phase IA (raw wastewater).

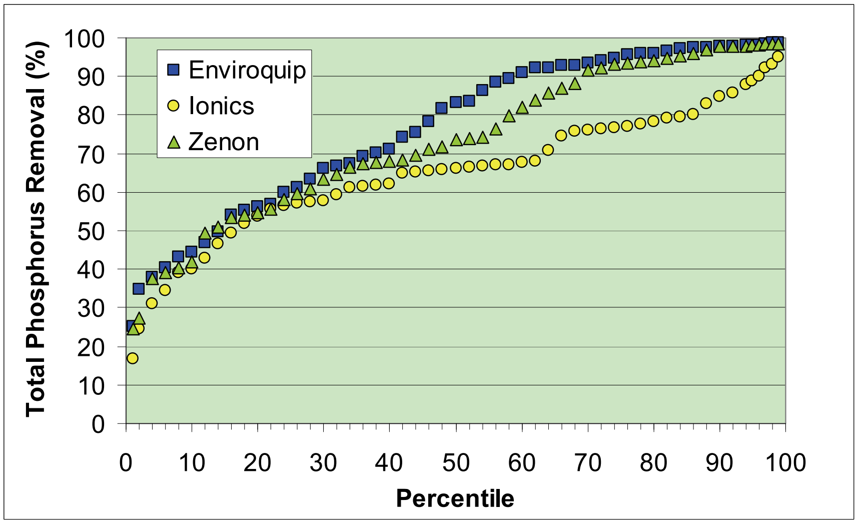

Figure 3.19. Total phosphorus removal efficiency distributions during Phase IA (raw wastewater).

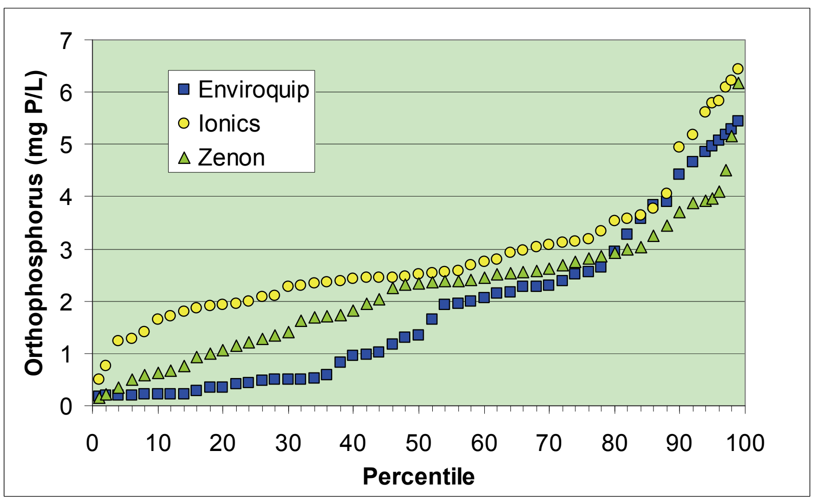

Figure 3.20. Effluent (permeate) orthophosphorus distributions during Phase IA (raw wastewater).

Color. Effluent data for color are shown in Figure 3.21. Color was not measured in the raw influent. The data indicate that the permeate color varied considerably on a relative scale. City and County of Honolulu, Environmental Branch, Treatment and Disposal Division (T&D) has a goal to reduce effluent color to less than 20 Pt-Co units, which is indistinguishable from the value for potable groundwater. It is apparent that the MBRs were not able to meet this goal and that color values ranged from about 25 to 70. At values of about 40 Pt-Co, there is a readily identifiable light brownness in the water. The service area for the Honouliuli WWTP is large, and the influent is quite septic and dark. In addition, this treatment plant is a major regional septage receiving station and also treats all of the primary and secondary sludges from another treatment plant (Wahiawa), which does not have solid-handling facilities. Figure 3.21 indicates that the performances of the three different types of MBRs are very comparable.

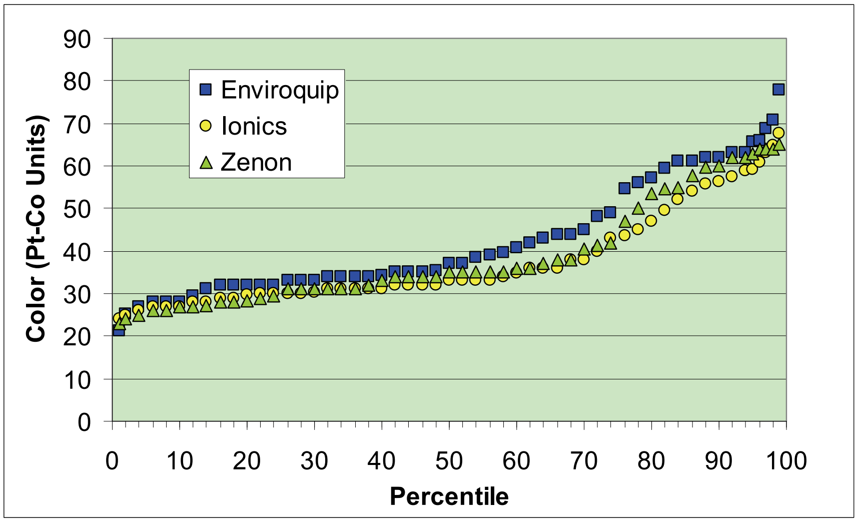

Figure 3.21. Effluent color value distributions during Phase IA (raw wastewater).

Turbidity. Considerable difficulties in obtaining accurate turbidity data were encountered during this study. The turbidity meters provided on each MBR pilot system were time consuming to maintain, and thus the ENV personnel did not consistently clean and calibrate them. The consequence of this neglect was that many inaccurate turbidity data were obtained. Only data collected when the turbidity was known to be calibrated are reported herein. Turbidity measurements were also made at the UH lab on composite samples; however, even these measurements were found to be difficult because of the extremely low values that are common for membrane permeate. Effluent data for turbidity for Phase IA are shown in Figure 3.22. The data show the very low values of permeate turbidity that are typical for MBR systems. The figure indicates that more than 90% of the turbidity values are less than 0.1 NTU for each of the MBRs and that the performances of the three different types of MBRs are somewhat different. However, since all of the values are so low, it is difficult to infer anything from the differences. The turbidity value of 0.2 NTU (achieved 95% of the time) is significant, since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon National Water Research Institute (NWRI) guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, while membrane-filtered effluents require only 80 mW-s/cm^2. Based on the data for Phase IA, these MBRs would qualify for the reduced UV disinfection dosage.

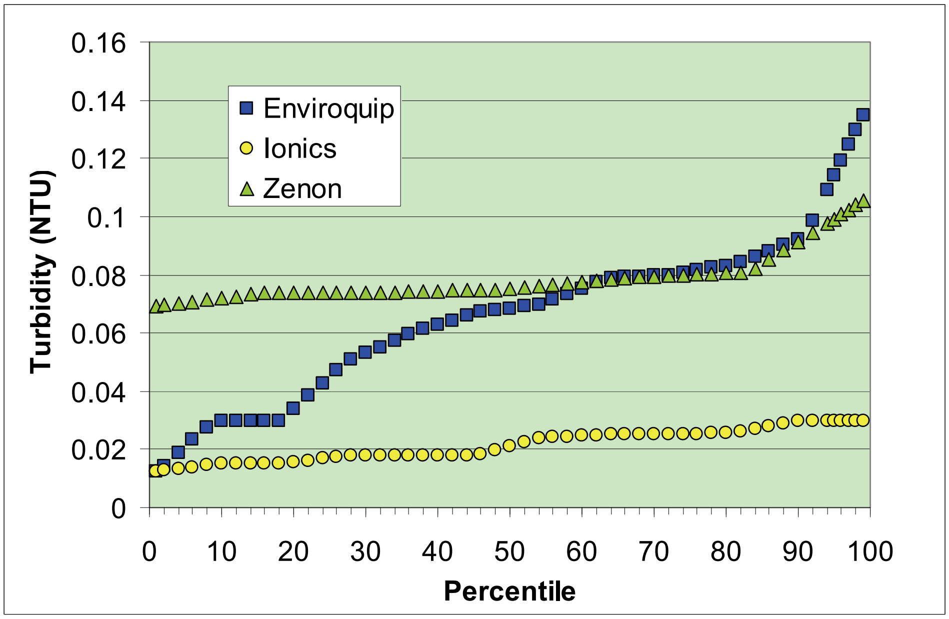

Figure 3.22. Effluent (permeate) turbidity distributions during Phase IA (raw wastewater).

UVT. Influent and effluent UVT_{254} data are shown in Figures 3.23 and 3.24, respectively. The data indicate that the raw wastewater feed had a low UVT of between 15 and 45%, with an average of about 30%, indicating a large quantity of UV-absorbing material. Figure 3.24 shows the very high values of permeate UVT that are typical for MBR systems. The figure indicates that more than 90 to 95% of the UVT values are greater than 65% for each of the MBRs and that the performances of the three different types of MBRs are very comparable. The UVT value of 65% is significant, since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, while membrane-filtered effluents require only 80 mW-s/cm^2. Based upon the data for Phase IA, these MBRs would qualify for the reduced UV disinfection dosage.

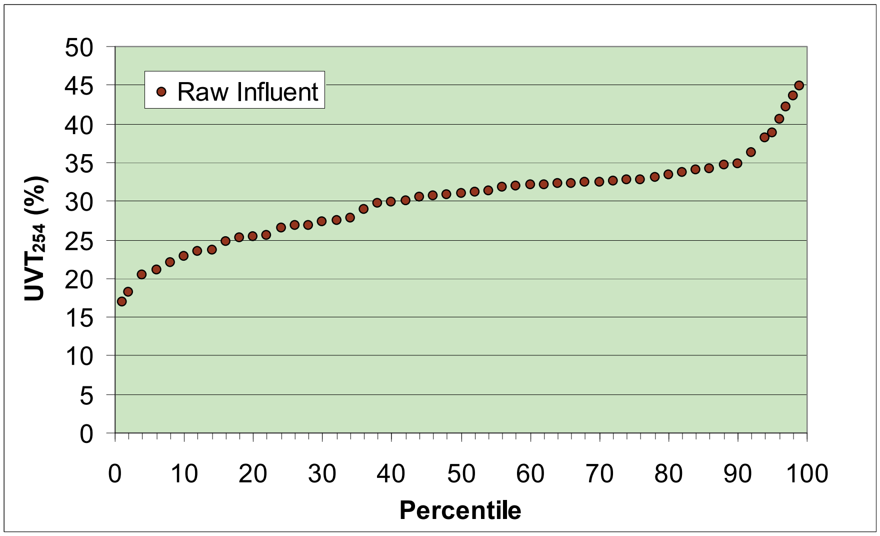

Figure 3.23. Raw influent UVT_{254} distribution during Phase IA.

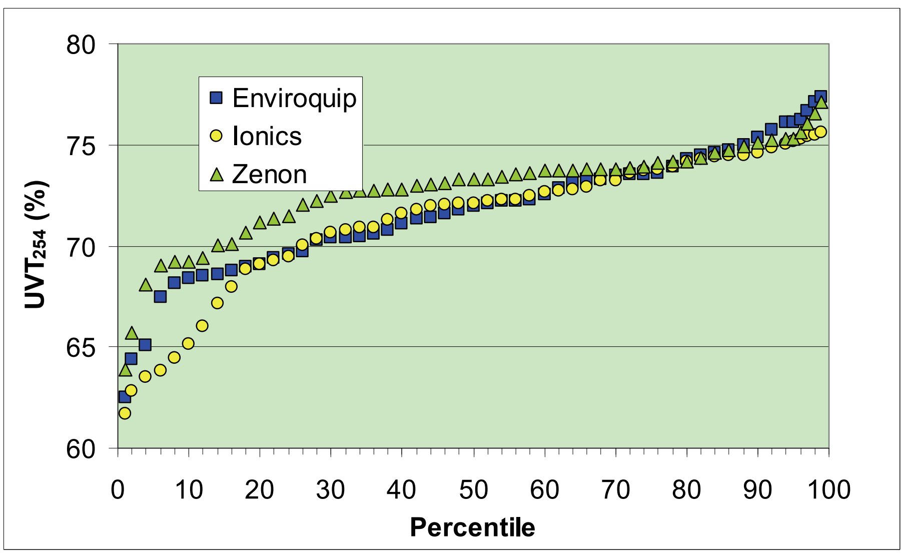

Figure 3.24. Effluent (permeate) UVT_{254} distributions during Phase IA (raw wastewater).

TDS. Influent, effluent, and TDS removal efficiency data are shown in Figures 3.25, 3.26, and 3.27, respectively. The data for phases IA, IB, and IC are included in this section. The data indicate a decreasing trend in TDS during Phase IA from approximately 950 to 700 mg/L. The centrate feed (Phase IB) TDS varied between approximately 850 and 1050 mg/L. The TDS was lowest during primary effluent feed (Phase IC), ranging from 650 to 750 mg/L. Figure 3.26 shows the permeate TDS data, which are difficult to distinguish from the influent data. Figure 3.27 was created to examine the differences between all pairs of TDS data points. The data indicate that the TDS sometimes increases and sometimes decreases during MBR treatment. During treatment of raw wastewater, the TDS seemed to either increase or decrease by approximately 50 to 100 mg/L, with deceases somewhat more common than increases. During treatment of centrate feed, the TDS nearly always decreased and by a larger amount (mostly 100 to 200 mg/L). During the treatment of primary effluent, the TDS nearly always increased by 50 mg/L or less.

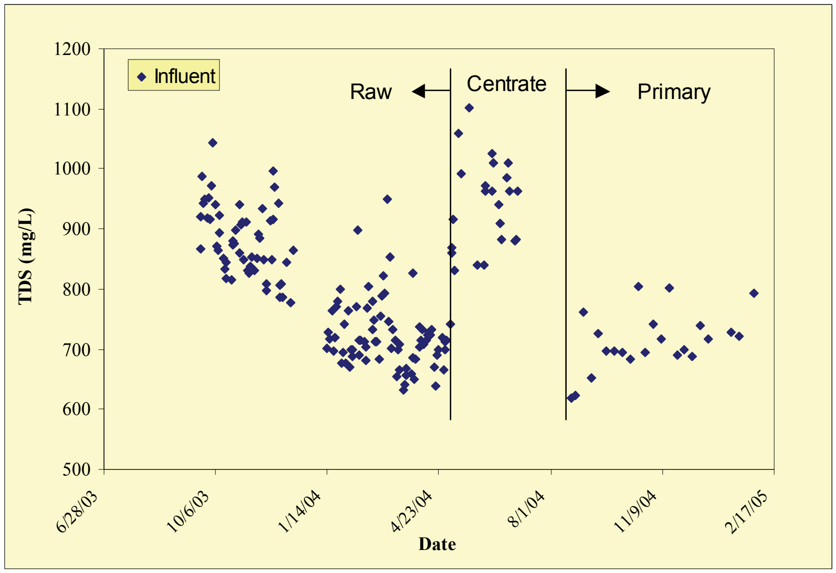

Figure 3.25. Raw influent TDS concentration during Phases IA, IB, and IC.

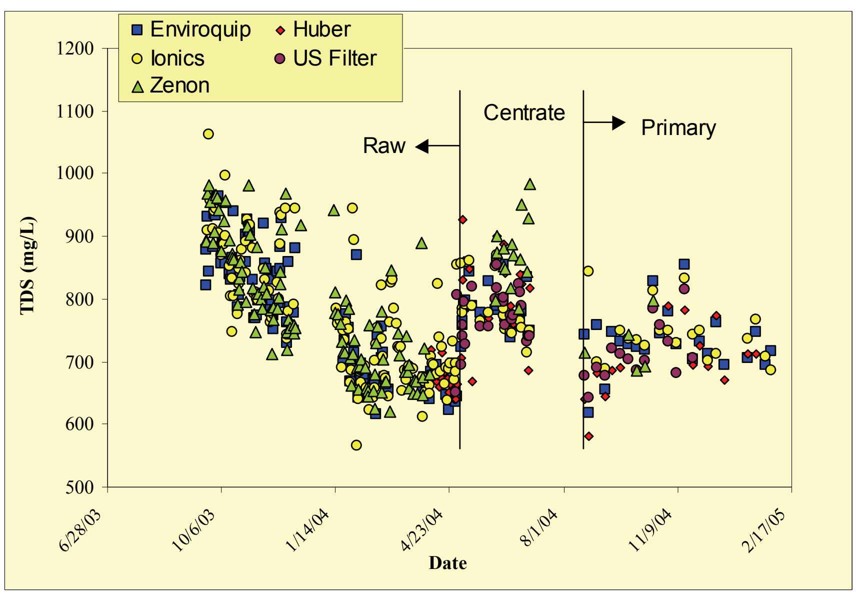

Figure 3.26. Effluent (permeate) TDS concentrations during Phases IA, IB, and IC.

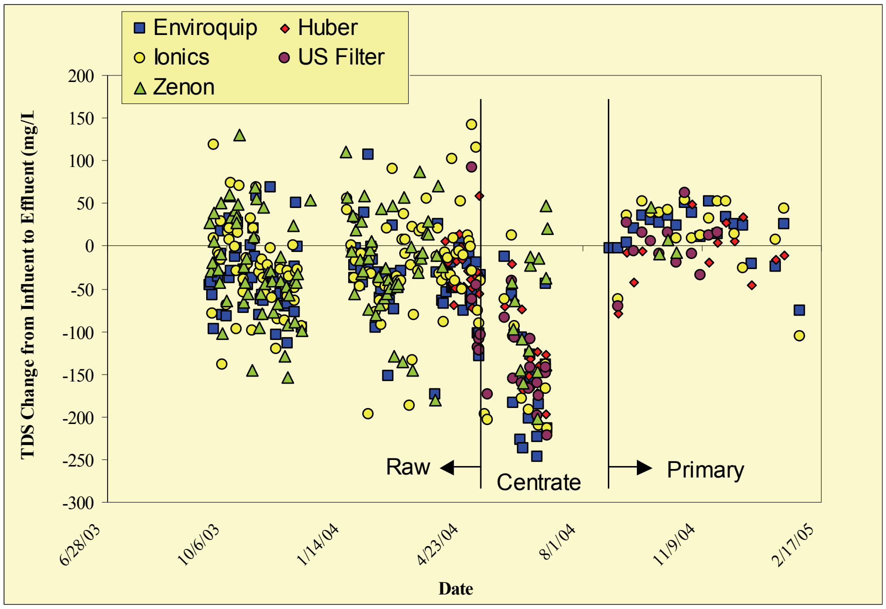

Figure 3.27. Calculated differences between influent and effluent (permeate) TDS concentrations during Phases IA, IB, and IC.

O&G. Influent and effluent O&G data are shown in Figures 3.28 and 3.29, respectively. The data indicate that the raw wastewater feed contained O&G concentrations between less than 10 mg/L and nearly 50 mg/L. Most MBR manufacturers state that up to 50 m of O&G/L is acceptable for MBR treatment. Higher concentrations could cause enhanced fouling rates. The effluent data indicate that O&G is removed well in the MBR systems with undetectable concentrations about 35% of the time and in those with less than 5 mg/L more than 90% of the time. The performances of the three different types of MBRs were very comparable.

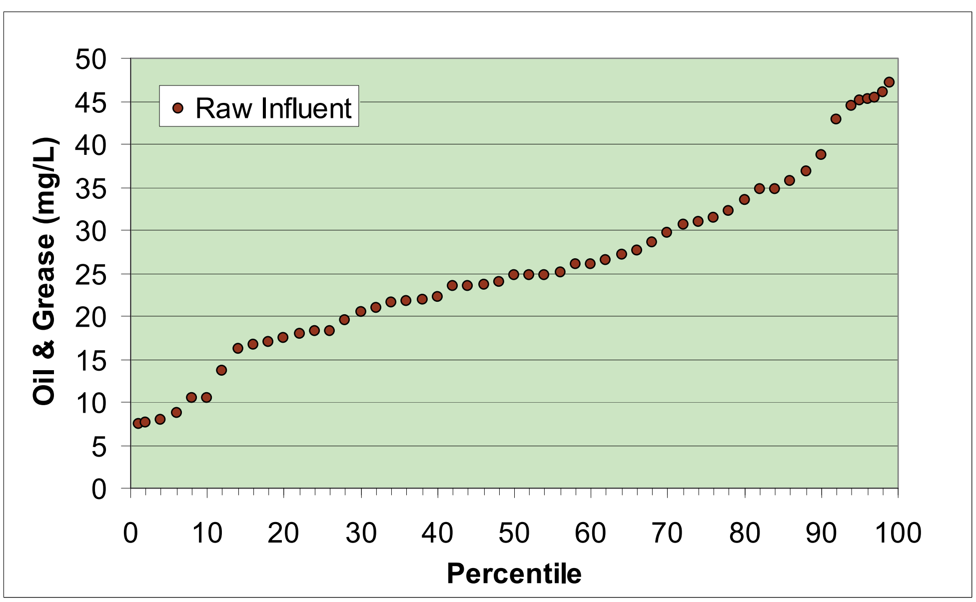

Figure 3.28. Raw influent O&G distribution during Phase IA.

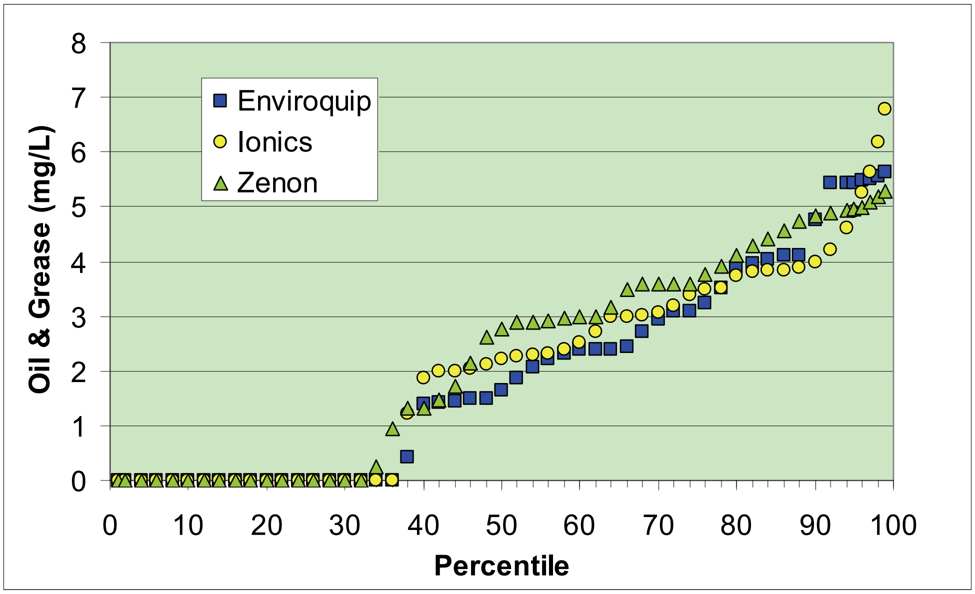

Figure 3.29. Effluent (permeate) O&G distributions during Phase IA (raw wastewater).

Fecal coliform and coliphage. Fecal coliform and coliphage were not detected in the effluent from the MBRs with the exception of a few events that were subsequently traced to sample contamination at the pilot site. Minimum, maximum, and average values for the influent are shown in Table 3.1. The data indicate one of the great benefits of MBRs, which is that they provide a positive barrier to microbes that are larger than the nominal membrane pore size. Since fecal coliform are about 1.0 μm, they do not pass through to the permeate. Some bacteria and viruses are smaller than the membrane pores and can pass through, so MBRs do not provide sterilization and must still be disinfected prior to reuse applications where human contact is possible. However, in these situations, disinfection strength may be reduced compared to other treatment scenarios due to the low concentration of solids and organic disinfectant-consuming materials.

Table 3.1. Influent and effluent fecal coliform and coliphage during Phase IA (raw wastewater)

	Value for concn of:			
Type of Phase IA value	**Fecal coliform(CFU/100 mL) in influent**	**Fecal coliform(CFU/100 mL) in effluent (all)**	**Fecal coliphage(PFU/100 mL) in influent**	**Fecal coliphage(PFU/100 mL) in effluent (all)**
Minimum value	3.0×10^6	<1	8.0×10^4	<1
Maximum value	1.1×10^8	3	7.3×10^6	<1
Avg. value	3.9×10^7	<1	4.8×10^5	<1

Alkalinity. Alkalinity was measured approximately monthly. Table 3.2 shows the alkalinity data collected during Phase IA. The data indicate that alkalinity was sufficient in the raw wastewater and that there was alkalinity remaining in the MBR permeates.

Table 3.2. Influent and effluent (permeate) alkalinity data for Phase IA (raw wastewater)

	Concn of $CaCO_3$ (mg/L) in:			
Date (mo-day-yr)	Influent	Enviroquip effluent	Ionics effluent	Zenon effluent
10-28-03	224	116	68	109
11-25-03	275	251	256	159
12-04-03	270	223	179	254
1-26-04	198	89	74	47
2-24-04	194	132	83	159
Avg.	232	162	132	146

Overall average water quality and removal efficiencies. Table 3.3 gives the overall average values of influent and effluent for all the water quality parameters discussed above. Table 3.3 also shows the average removal efficiencies for the same parameters where appropriate.

Table 3.3. Average water quality data and removal efficiencies (in parentheses) during Phase IA (raw wastewater) and after Phase I (Huber and Koch)

	Value for:					
Analyte	**Influent**	**Enviroquip**	**Ionics**	**Zenon**	**Huber[a]**	**Koch[a]**
BOD_5 (mg/L)	269	2.6 (99.0%)	2.3 (99.1%)	2.0 (99.3%)	1.2 (99.7%)	1.5 (99.4%)
TSS (mg/L)	227	1.2 (99.5%)	1.5 (99.3%)	1.3 (99.4%)	0.8 (99.8%)	1.1 (99.7%)
TOC (mg/L)	57	9.0 (84.2%)	7.2 (87.5%)	7.1 (87.5%)	6.5 (95.0%)	7.9 (86.6%)
COD (mg/L)	NA	NA	NA	NA	20 (98.6%)	14.3 (97.3%)
O&G (mg/L)	25.3	1.9	2.1	2.2	<1.0	<1.0
Nitrogen, total (mg of N/L)	39.9	15.8 (60%)	15.9 (60%)	15.1 (62%)	14.5 (76%)	14.1 (62%)
Ammonia (mg of N/L)	26.7	10.5	2.7	5.2	0.24	0.2
Nitrate (mg of N/L)	NA	2.9	12.2	9.5	NA	13.9
Phosphorus, total (mg of P/L)	7.1	1.8 (75%)	2.4 (66%)	1.8 (75%)	3.6 (65%)	3.5 (45%)
Ortho-phosphorus (mg of P/L)	NA	1.8	2.4	1.9	NA	3.8
Color (Pt-Co)	NA	42	37	39	33	24
UVT_{254} (%)	30.1	71.6	71.2	72.6	71	75
Turbidity (NTU)	NA	0.07	0.02	0.08	0.14	0.13
Fecal coliform (CFU/100 mL)	3.9×10^7	<1	<1	<1	<1	<1
Coliphage (PFU/100 mL)	4.8×10^5	<1	<1	<1	<1	<1
Alkalinity (mg of $CaCO_3$/L)	232	162	132	146	126	47

[a]Effluent results based upon data collected after Phase IA and removal efficiencies determined based upon measured influent data (from after Phase IA).

Stress testing. Two large storms in November and December 2003 allowed for unplanned stress testing of the Enviroquip, Ionics, and Zenon MBR pilot units. During the first heavy rains in late November 2003, the influent TSS reached a 24-h average of 1120 mg/L (see Figure 3.30), which did not seem to have any effect on effluent TSS, BOD_5, or turbidity (see Figures 3.31, 3.32, and 3.33). Larger storms in early December 2003 caused major problems at the Honouliuli WWTP, including failure of its sludge stabilization process, forcing it to recycle all of its primary solids through the treatment plant for several days. This event caused the influent TSS to the pilot MBRs to increase at one point to over 11,000 mg/L and the BOD_5 to increase to over 1000 mg/L (24-h composites). Under these conditions, the MBRs became anaerobic and treatment performance declined dramatically. Figures 3.31 and 3.32 show that effluent TSS and BOD_5 increased to over 10 and over 20 mg/L, respectively. At the same time, effluent turbidity increased to over 20 or even 60 NTU. These were very unusual situations and do not reflect expected conditions at full-scale treatment plants. However, these data do show what can happen if aeration capacity is lost in an MBR. It should be noted that, after these events, the membrane were fouled to the point of inoperability and had to be chemically cleaned prior to restarting. However, the membranes did not suffer any permanent fouling due to these events.

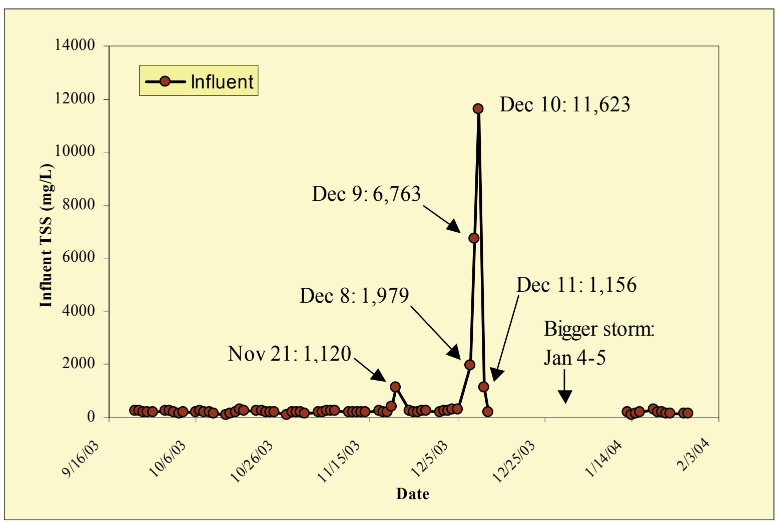

Figure 3.30. Influent suspended solids during "stress tests."

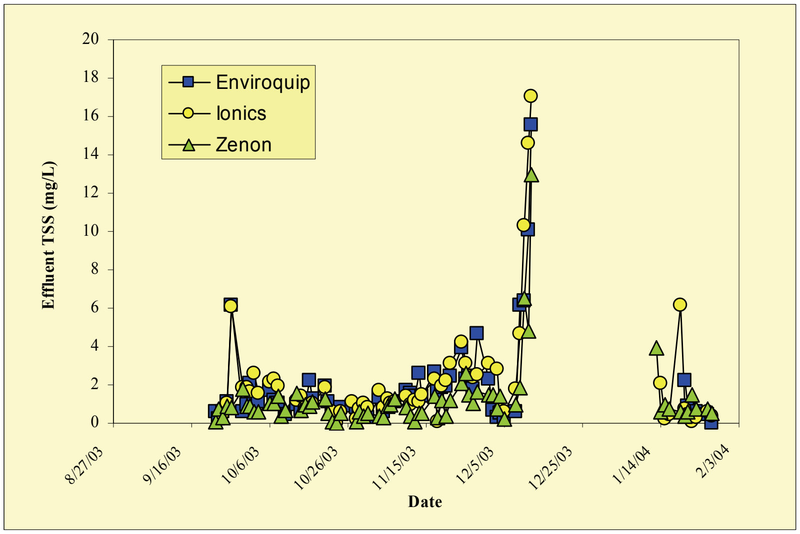

Figure 3.31. Effluent suspended solids during "stress tests."

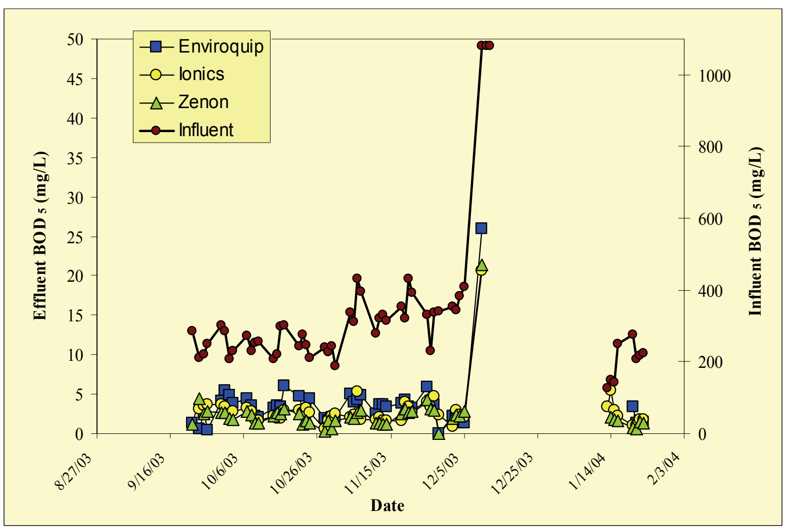

Figure 3.32. Influent and effluent BOD_5 during "stress tests."

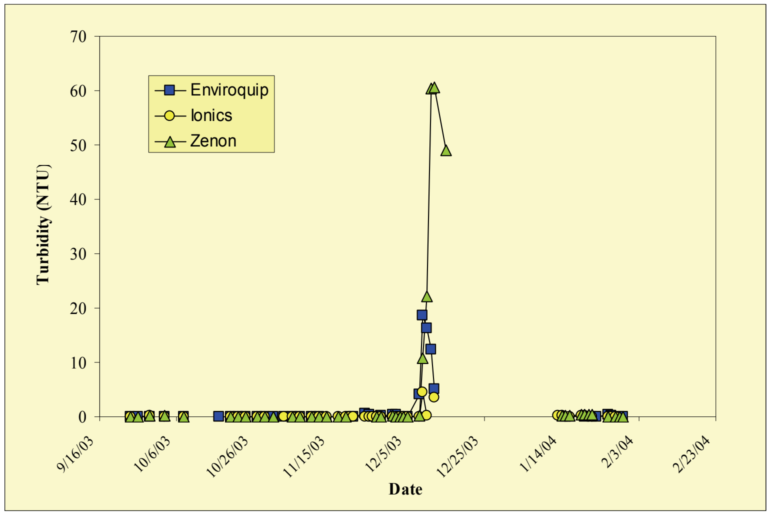

Figure 3.33. Effluent turbidity during "stress tests."

3.2.1.3 Process Operating Data for Koch

The Koch MBR did not arrive until after side-by-side testing of the other five MBRs was completed. A 3-mm fine screen was used for pretreatment of raw wastewater in this phase. The CCH is interested in the treatment of raw wastewater for applications such as treatment plant expansion, treatment plant upgrades for water recycling or nutrient removal, and satellite water recycling. The main water quality goals are to reduce BOD and TSS to less than 5 mg/L and turbidity to less than 0.2 NTU, keep UVT greater than 65%, and have <1 fecal coliform CFU/100 mL. There are no nutrient removal goals. The Koch pilot unit began operations on December 8, 2005. Instantaneous grab and 24-hour composite samples were collected 3 days a week and analyzed for a suite of analytes. The Koch unit was operated at essentially steady state during this period. The unit experienced failure of two pumps during this period and was out of service for 16 days in April for repairs (excessive grit in progressive cavity pumps). The MBR was restarted on April 28, 2006, and it took until May 22 for the MLSS to regain the steady-state value of 11 g/L. The Koch pilot MBR was serviced in the first week of June. Repair consisted of removal of the membrane cassette, external chemical cleaning, and replacement. In September 2006 the Koch pilot unit was serviced again, which included replacement of the entire membrane cassette. Table 3.3 gives the overall average values of influent and effluent water quality parameters currently being routinely monitored. The average removal efficiencies for the same parameters are also shown where appropriate. During this same period, the approximate average values of permeate flux, TMP, MLSS, mixed liquor volatile suspended solids (MLVSS), and DO were 10 GFD, −1.0 psi, 10 g/L, 8.4 g/L, and 1.5 mg/L, respectively. Overall, the effluent (permeate) water quality produced by the Koch MBR was excellent by industry standards for secondary effluent and/or filtered secondary (tertiary) effluent.

The Koch MBR uses Puron technology, which is a supported hollow-fiber configuration. The membranes are potted only at the bottom of the module and have a rigid support that allows the membranes to stand up straight. The microfiltration membranes have a pore size of 0.1 µm. The system is similar to the previously tested hollow-fiber MBRs in that it utilizes a periodic backflushing for maintenance cleaning (every 5 min) and cyclic aeration (10 s on, 20 s off). The Koch MBR operates at three different flux rates that vary during the day (see Figure 3.34). These include minimum flux (F_{min}), optimum flux (F_{opt}), and maximum flux

(F_{max}). Figure 3.35 shows how the TMP increases when the flux increases and vice versa. The membranes were recovery cleaned in place once in mid-February by using a programmed protocol incorporating 1% hypochlorite and 10% citric acid solutions. The cleaning did not seem to have any effect on TMP. MBRs are generally operated by maintaining a target MLSS rather than a target SRT. The Koch MBR pilot unit has an online solid meter and automatic wasting system designed to maintain a solid set-point, in this case 10 g/L. Figure 3.36 shows how it took about 30 days for the MBR to build up solids from the initial seed value of about 3000 mg/L to approximately 11,000 mg/L. Since then, the system has maintained a steady MLSS value. Figure 3.37 shows an inverse trend of DO relative to MLSS. It appears that the MBR is capable of maintaining a DO of 1.0 to 1.5 mg/L at an MLSS of 11 g/L. The MBR has DO control and should be able to provide the same DO concentration at higher solid concentrations.

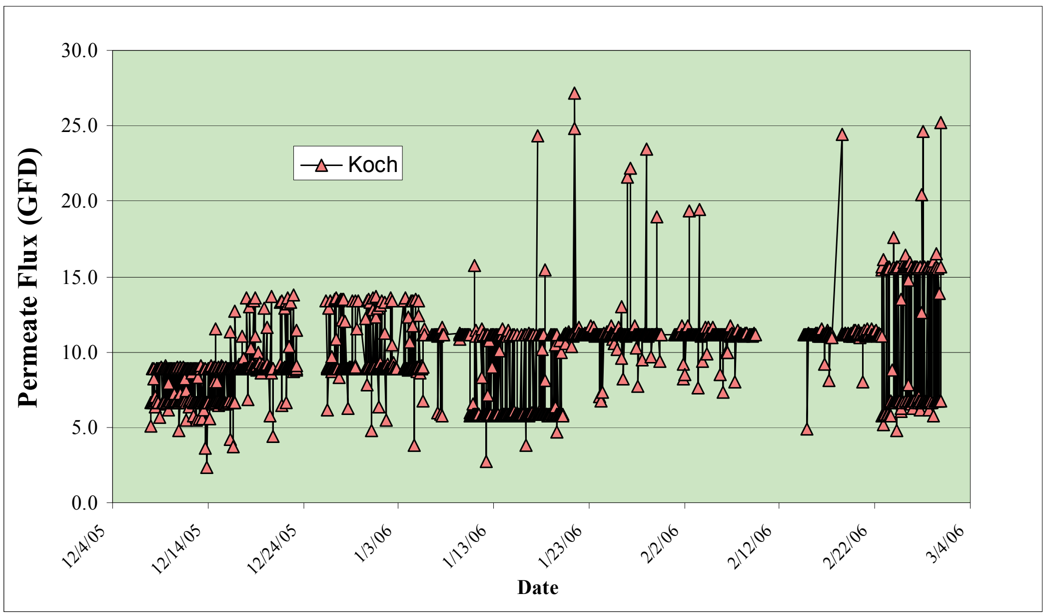

Figure 3.34. Permeate flux for Koch MBR (raw wastewater).

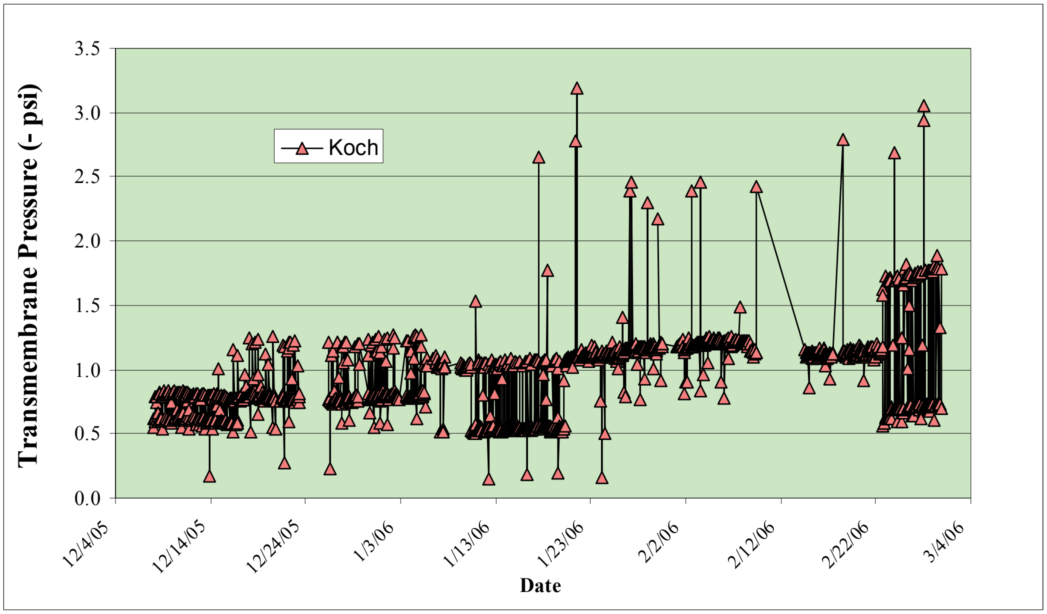

Figure 3.35. TMP in Koch MBR (raw wastewater).

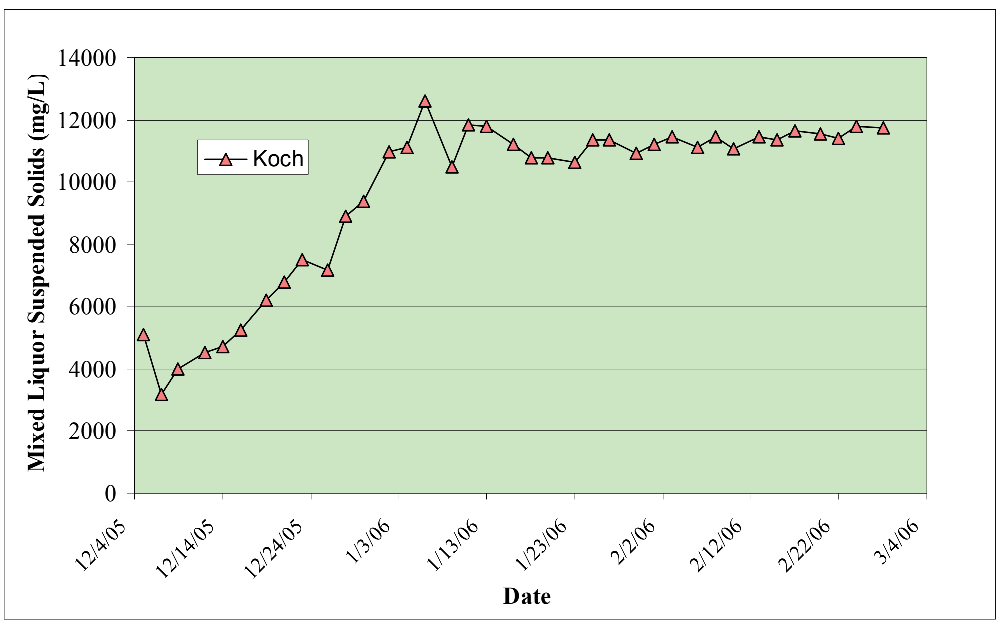

Figure 3.36. Mixed liquor TSS concentrations in Koch MBR (raw wastewater).

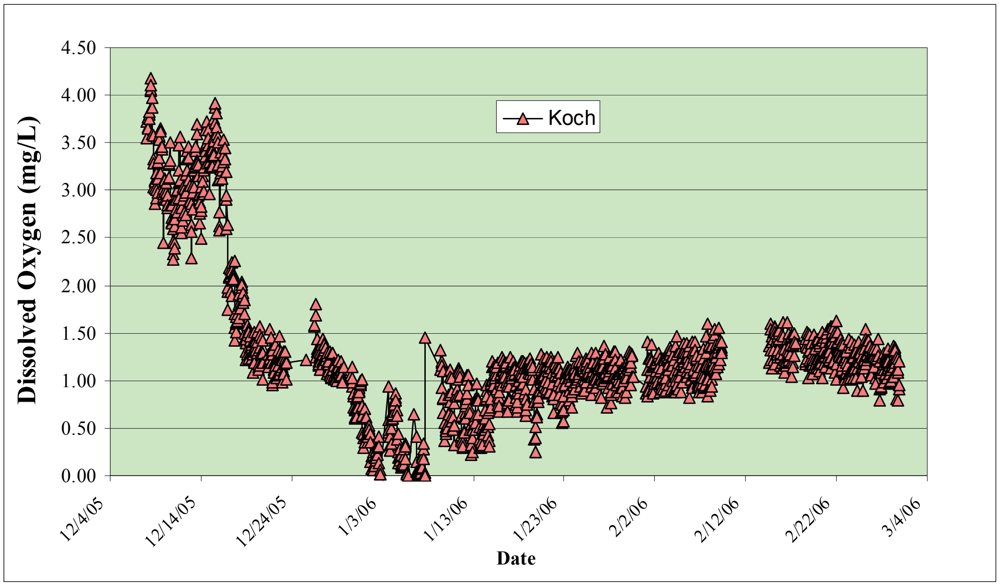

Figure 3.37. DO concentrations in Koch MBR (raw wastewater).

3.2.1.4 Water Quality Data for Koch

The water quality data are presented in Figures 3.38 through 3.55 and Tables 3.3 and 3.4. Overall, the effluent (permeate) water quality produced by the Koch MBR was excellent by industry standards for secondary effluent and/or filtered secondary (tertiary) effluent. The data are presented in the form of distributions rather than time-course plots. In this case, the data sets are analyzed to determine the percentage of the data points that are smaller than a given numerical value. This arrangement allows the reader to easily see the overall distribution of the data as well as get a feel for the maximum, minimum, and average values. Overall average influent and effluent values and overall removal efficiencies for all of the water quality parameters analyzed are reported in Table 3.3 above.

BOD. Influent and effluent BOD_5 data are shown in Figures 3.38 and 3.39, respectively. The data indicate that the raw wastewater feed was of medium strength and that the BOD_5 varied between approximately 125 and 500 mg/L. In addition, approximately 80% of the data fall between 200 and 350 mg/L. Figure 3.39 shows the very low values of effluent BOD_5 that are typical for MBR systems. The figure indicates that approximately 70% of the BOD_5 values are less than 2 mg/L and that all of the values were less than 3.5 mg/L.

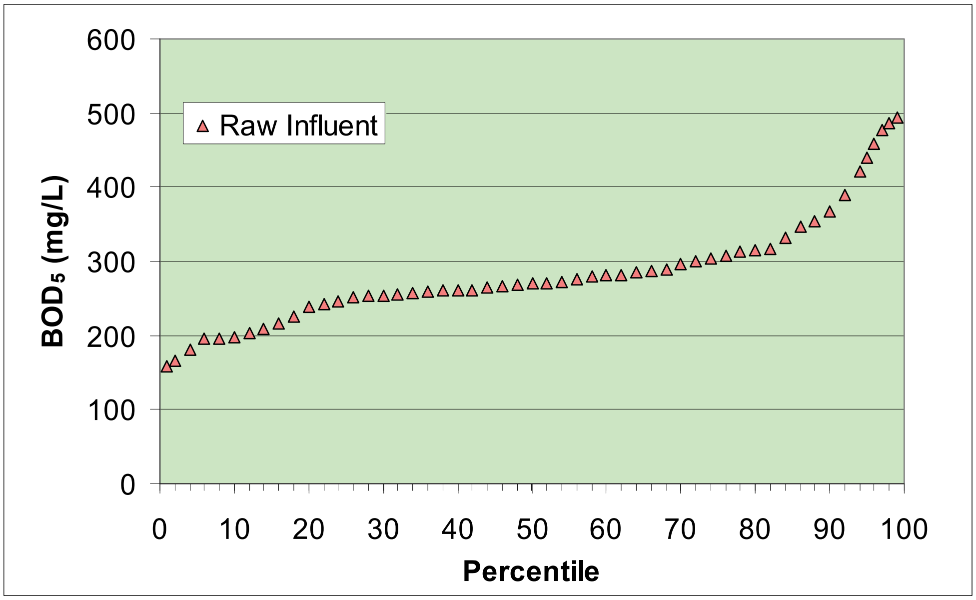

Figure 3.38. Raw influent BOD_5 concentration distribution during Koch testing.

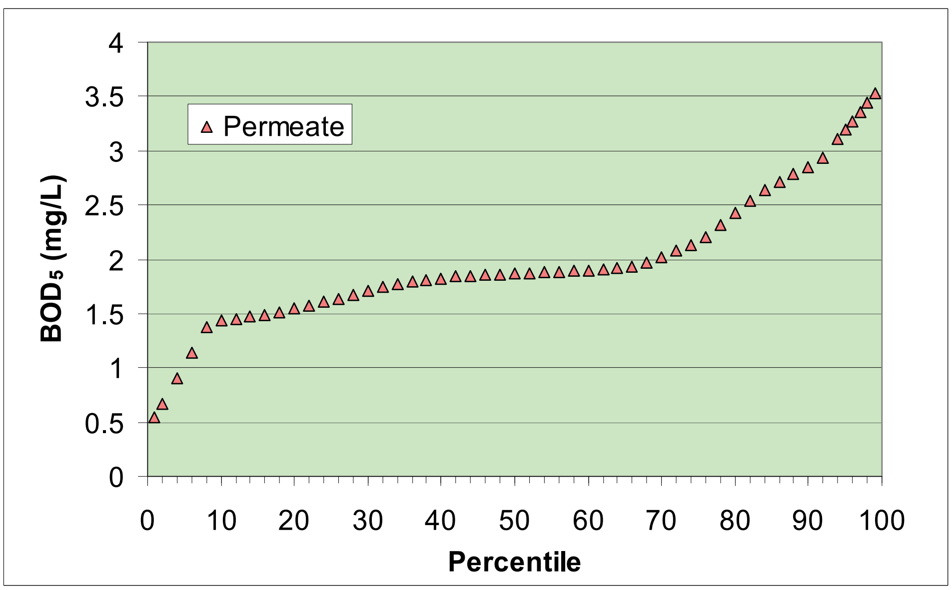

Figure 3.39. Effluent (permeate) BOD_5 concentration distribution for Koch MBR (raw wastewater).

TOC. Influent and effluent TOC data are shown in Figures 3.40 and 3.41, respectively. The data indicate that the TOC varied between approximately 30 and 110 mg/L. Figure 3.41 shows that the MBR permeates contain small yet significant amounts of organic carbon. Comparison of Figures 3.38 and 3.40 indicates that influent BOD_5 is approximately 400 to 500% larger than influent TOC, while comparison of Figures 3.39 and 3.41 indicates that effluent TOC is larger than effluent BOD_5. This finding means that a small amount of soluble organic matter that is not readily degradable as BOD_5 passes through the MBR systems. This amount is often denoted as soluble microbial products (SMP) that can be fractionated into carbohydrates, proteins, and lipids.

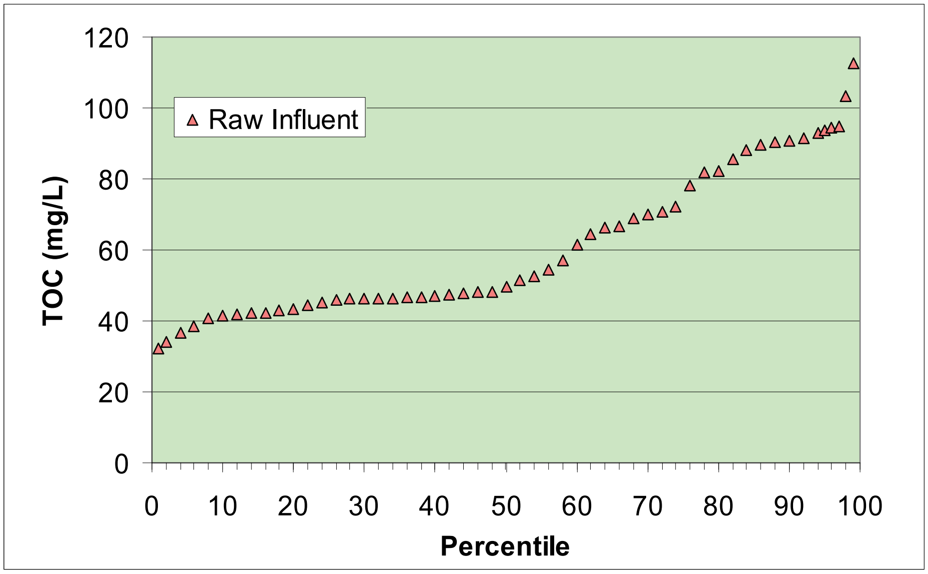

Figure 3.40. Raw influent TOC concentration distribution during Koch testing.

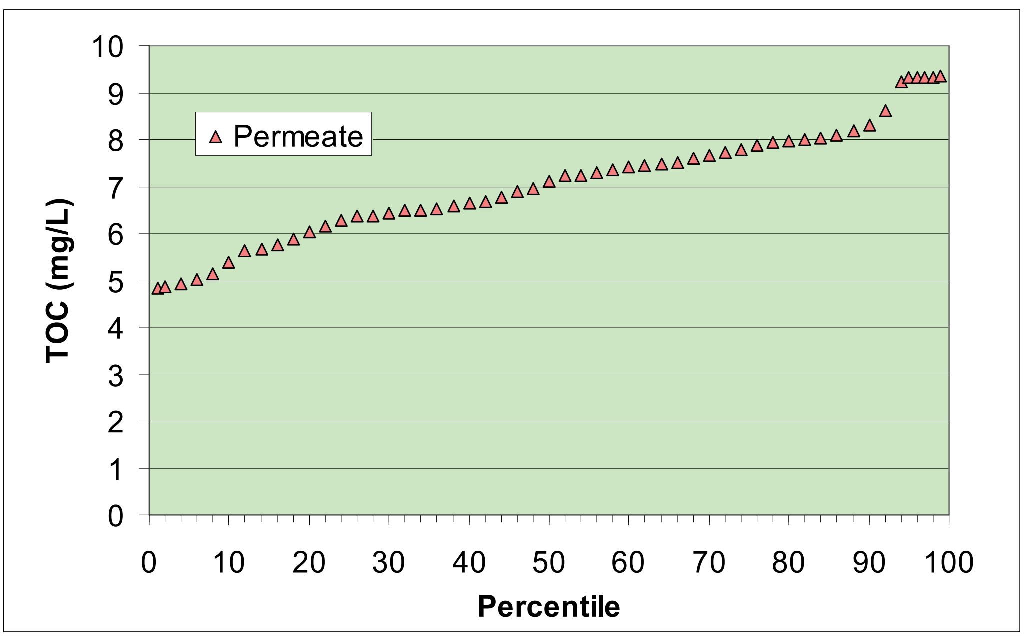

Figure 3.41. Effluent (permeate) TOC concentration distributions for Koch MBR (raw wastewater).

COD. Influent and effluent COD data are shown in Figures 3.42 and 3.43, respectively. The data indicate that the COD varied between approximately 300 and 1500 mg/L. Figure 3.43 shows the very low values of effluent COD that are typical for MBR systems. The figure indicates that approximately 100% of the COD values are less than 20 mg/L.

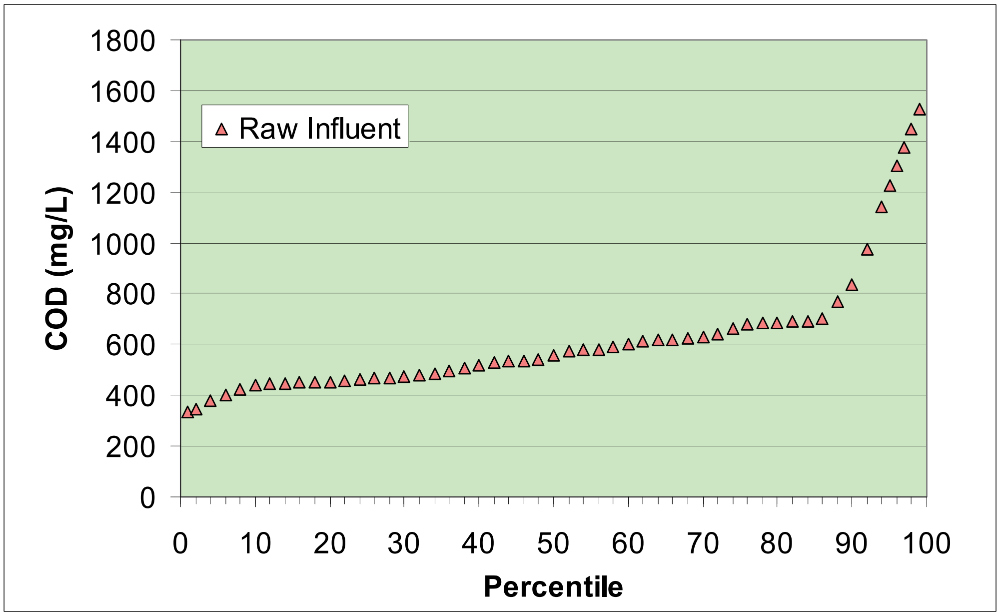

Figure 3.42. Raw influent COD concentration distribution during Koch testing.

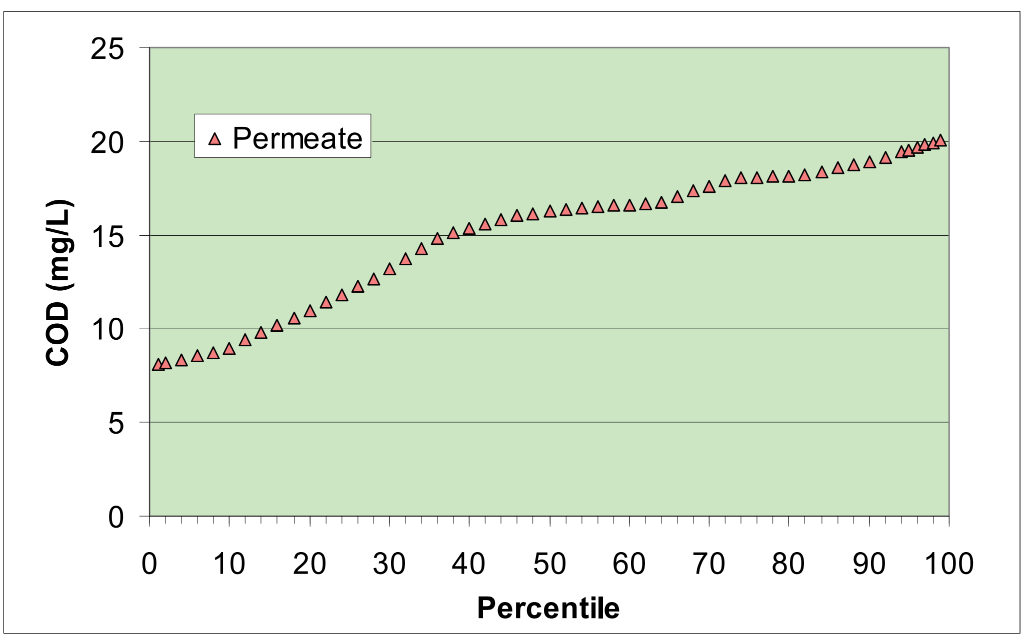

Figure 3.43. Effluent (permeate) COD concentration distributions for Koch MBR (raw wastewater).

TSS. Influent and effluent TSS data are shown in Figures 3.44 and 3.45, respectively. The data indicate that the raw wastewater feed was of medium strength and that the TSS varied between approximately 185 and 750 mg/L. In addition, approximately 80% of the data fall between 200 and 400 mg/L. Figure 3.45 shows the very low values of effluent TSS that are typical for MBR systems. The figure indicates that 90% of the TSS values are less than 3 mg/L and that approximately 70% are less than 2 mg/L.

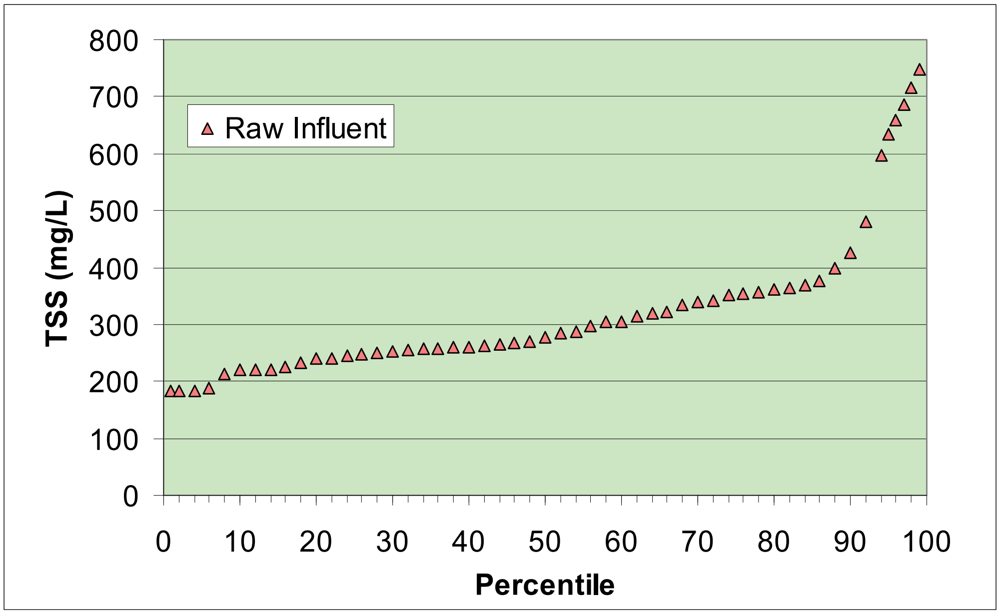

Figure 3.44. Raw influent TSS concentration distribution during Koch testing.

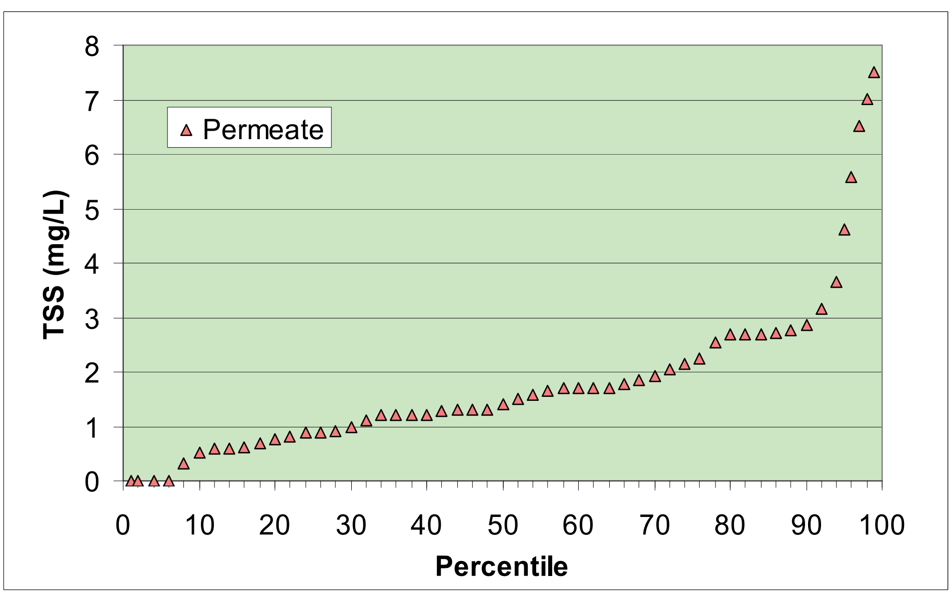

Figure 3.45. Effluent (permeate) TSS concentration distribution for Koch MBR (raw wastewater).

Nitrogen species. Influent and effluent data for total nitrogen are shown in Figure 3.46. Influent ammonia, effluent ammonia, and effluent nitrate data are shown in Figures 3.47, 3.48, and 3.49, respectively. The data indicate that the raw wastewater feed was of medium strength and that the total nitrogen varied between approximately 30 and 75 mg/L. In addition, approximately 95% of the data fall between 30 and 50 mg/L. Influent ammonia nitrogen varied from 17 to 33 mg/L, while effluent values were very low (90% less than 0.2 mg/L). Figure 3.46 indicates that the amount of total nitrogen remaining in the effluent varied from nearly zero to about 36 mg/L. Because the Koch MBR pilot is equipped with an anoxic zone and mixed liquor recycling system, the unit is capable of significant nitrogen removal. Figure 3.49 indicates that denitrification was initially limited but increased rapidly such that most effluent nitrate values are less than 5 mg/L.

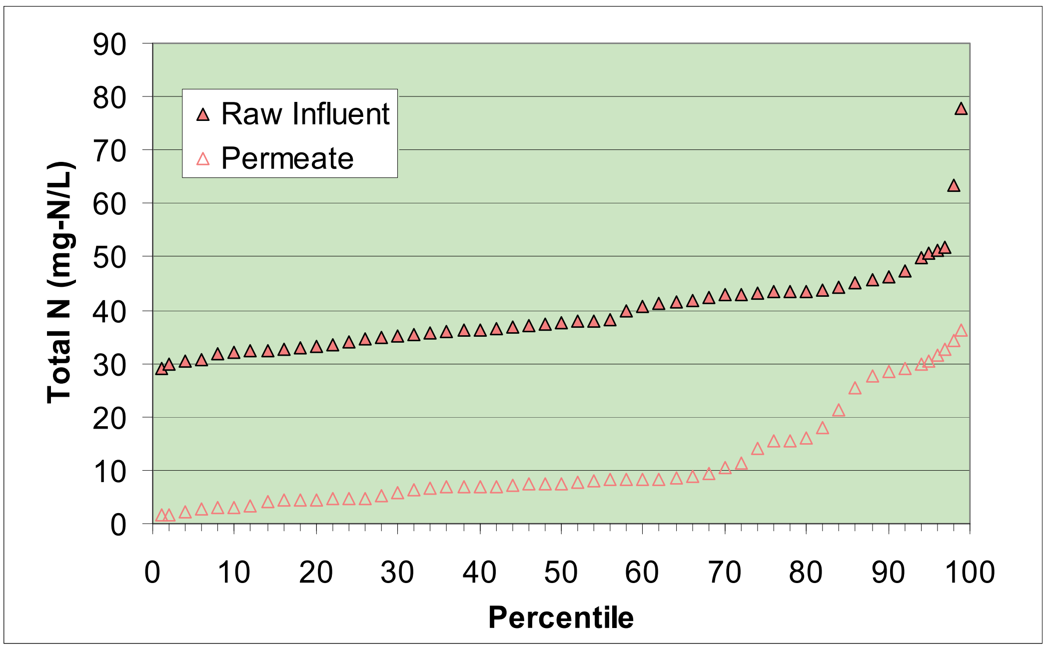

Figure 3.46. Influent and effluent total nitrogen concentration distributions during Koch testing.

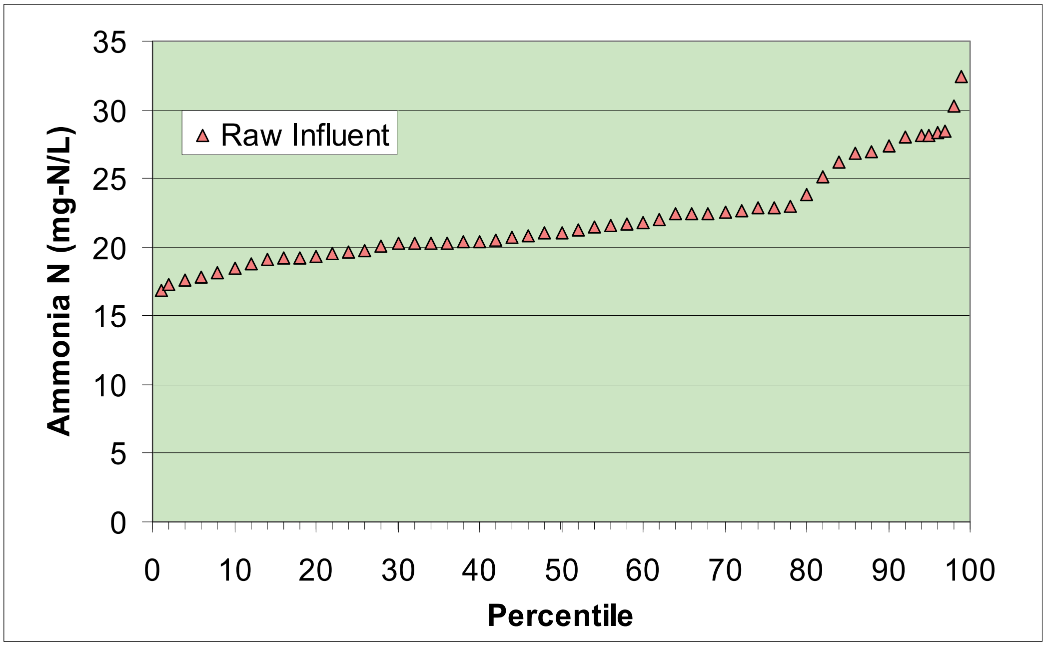

Figure 3.47. Raw influent ammonia nitrogen concentration distribution during Koch testing.

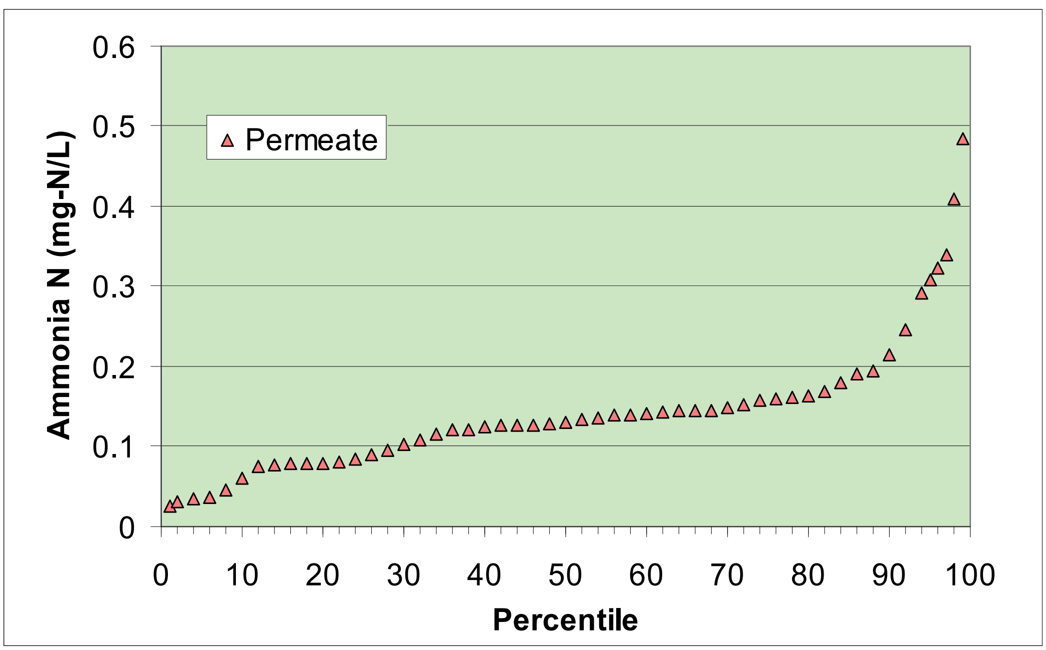

Figure 3.48. Effluent (permeate) ammonia nitrogen concentration distribution for Koch MBR (raw wastewater).

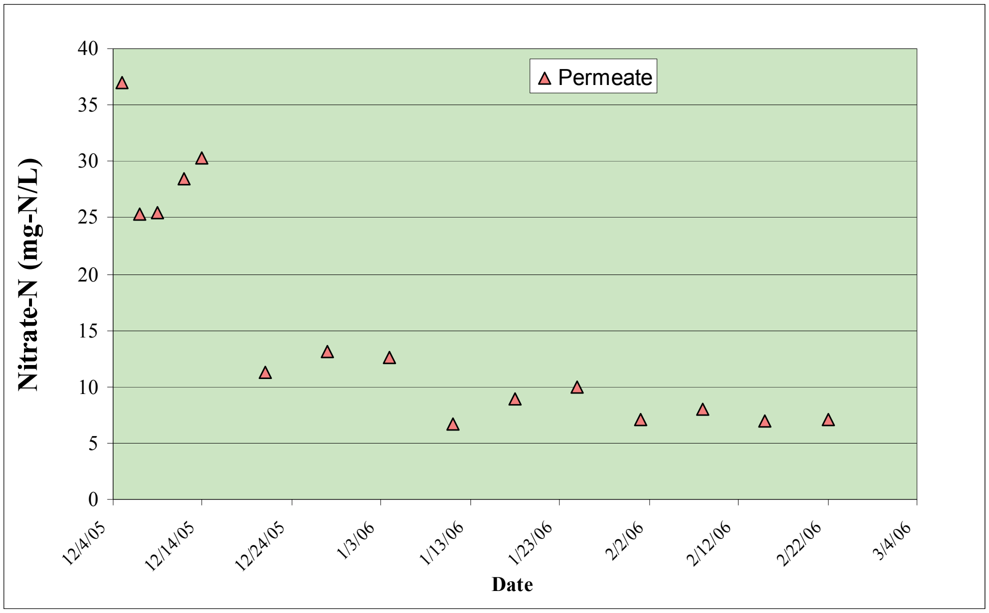

Figure 3.49. Effluent (permeate) nitrate nitrogen concentrations for Koch MBR (raw wastewater).

Phosphorus species. Influent and effluent data for total phosphorus are shown in Figure 3.50. The data indicate that the raw wastewater feed contained between approximately 4 and 12 mg of total phosphorus/L. Effluent total phosphorus varied from 2 to 6 mg/L. The Koch MBR pilot is not specifically set up for Bio-P removal or coagulant addition for chemical P removal. Therefore, the observed P removal can be attributed to normal biological uptake.

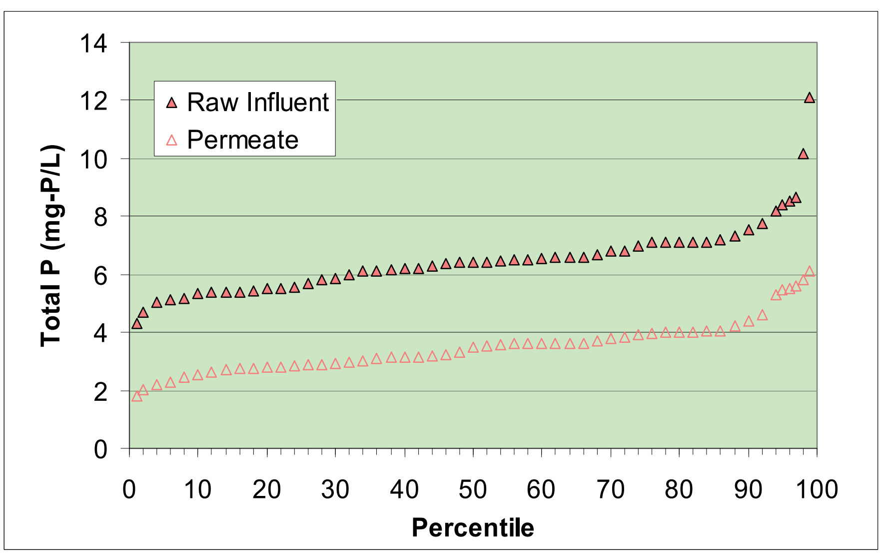

Figure 3.50. Raw influent total phosphorus concentration distribution during Koch testing.

Color. Influent and effluent data for color are shown in Figures 3.51 and 3.52. The data indicate that both the influent color and permeate color varied considerably on a relative scale. T&D has a goal to reduce effluent color to less than 20 Pt-Co units, which is indistinguishable from the value for potable groundwater. It is apparent that the MBRs were not able to meet this goal and that color values ranged from about 17 to 30. At values of about 40 Pt-Co, there is a readily identifiable light brownness in the water. At a value of color between 25 and 30 Pt-Co, one needs a piece of white paper as a backdrop to notice the color.

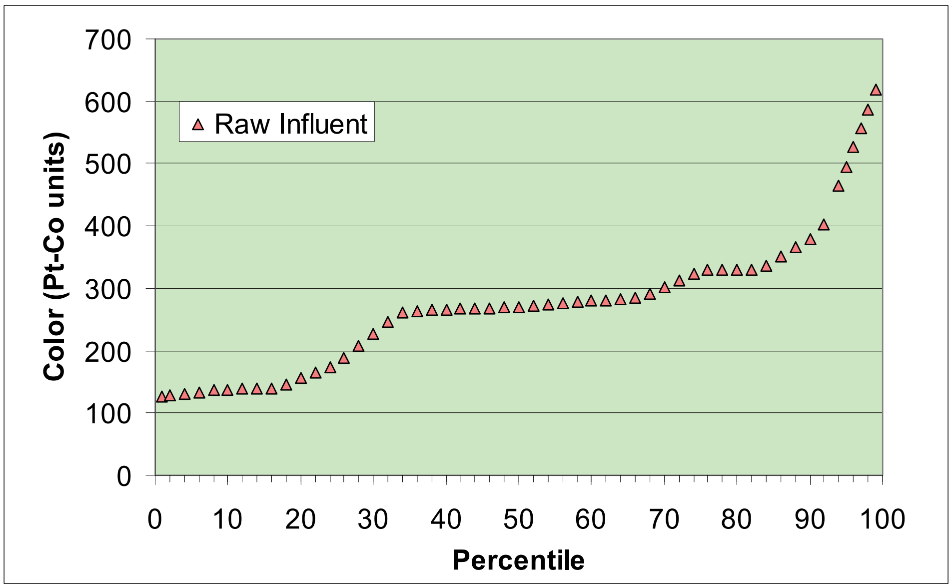

Figure 3.51. Raw influent color distribution during Koch testing.

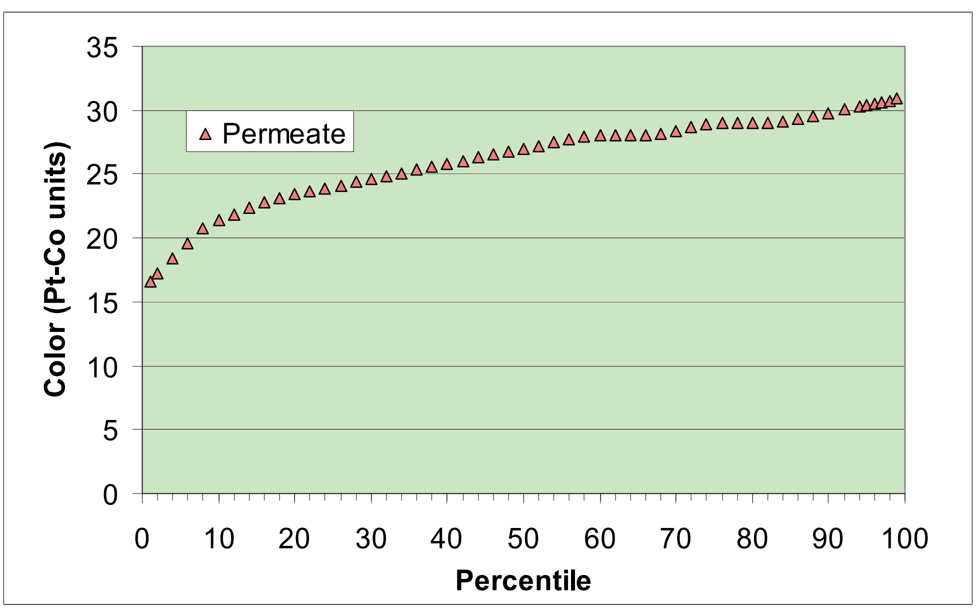

Figure 3.52. Effluent color distribution for Koch MBR (raw wastewater).

Turbidity. Effluent data for turbidity are shown in Figure 3.53. The data show the very low values of permeate turbidity that are typical for MBR systems. The figure indicates that the turbidity was variable during the period from start-up through the middle of January 2006. On January 19, 2006, the turbidity meter was recalibrated. Since then, the turbidity readings have consistently been below 0.10 NTU. It is unknown whether the values prior to that date are correct. The turbidity value of 0.2 NTU (achieved 95% of the time) is significant since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, whereas membrane-filtered effluents require only 80 mW-s/cm^2. Assuming that only the data after meter calibration are correct, the Koch MBR would qualify for the reduced UV disinfection dosage. The earlier data are assumed to be incorrect due to an out-of-calibration meter.

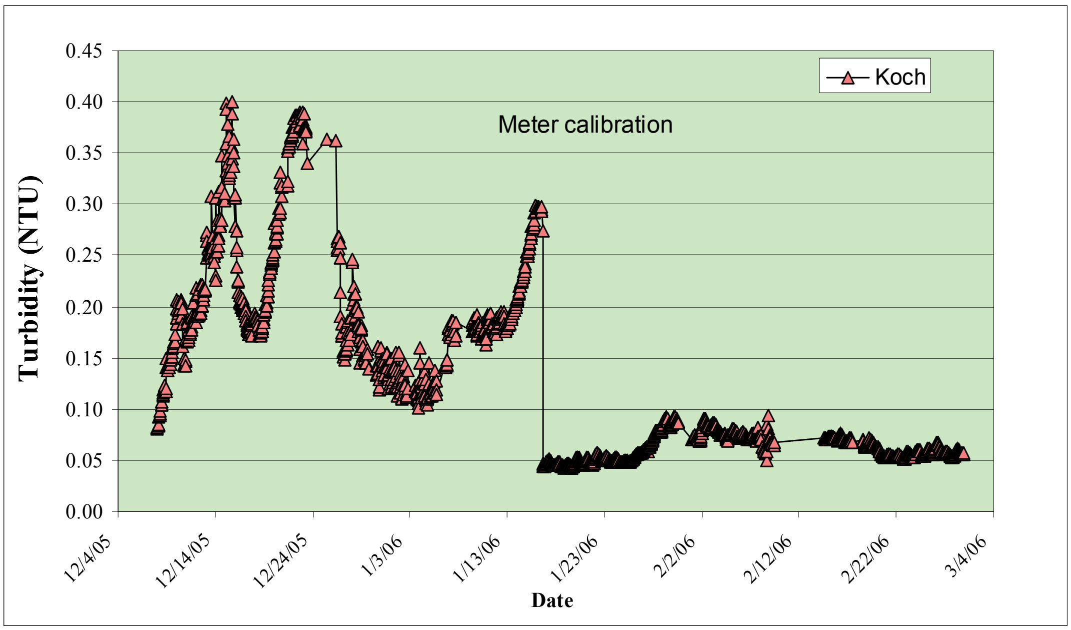

Figure 3.53. Effluent (permeate) turbidity values for Koch MBR (raw wastewater).

UVT. Influent and effluent UVT_{254} data are shown in Figure 3.54. The data indicate that the raw wastewater feed had a low UVT of between 20 and 50%, with an average of about 36%, indicating a large quantity of UV-absorbing material. Figure 3.54 shows the very high values of permeate UVT that are typical for MBR systems. The figure indicates that greater than 99% of the UVT values are greater than 70%. The UVT value of 65% is significant since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, whereas membrane-filtered effluents require only 80 mW-s/cm^2. Based upon the data thus far, the Koch MBR would qualify for the reduced UV disinfection dosage.

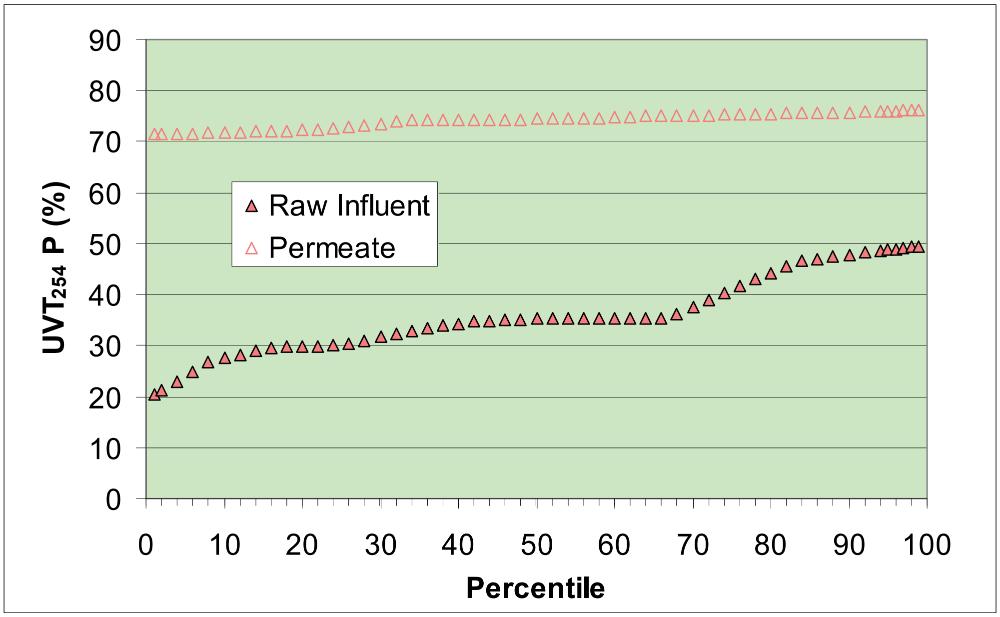

Figure 3.54. Raw influent and effluent (permeate) UVT_{254} distributions during Koch testing.

Fecal coliform and coliphage. Fecal coliphage was not detected in the effluent from the Koch MBR. Fecal coliform was detected in a few samples; however, this is thought attributable to sample contamination at the pilot site. Minimum, maximum, and average values for the influent are shown in Table 3.4. The data indicate one of the great benefits of MBRs, which is that they provide a positive barrier to microbes that are larger than the nominal membrane pore size. Since fecal coliform are about 1.0 µm, they are not able to pass through to the permeate. Some bacteria and viruses are smaller than the membrane pores and can pass through, so MBRs do not provide sterilization and must still be disinfected prior to reuse applications where human contact is possible. However, in these situations, disinfection strength may be reduced compared to other treatment scenarios due to the low concentration of solids and organic disinfectant-consuming materials.

Table 3.4. Influent and effluent fecal coliform and coliphage during Koch testing (raw wastewater)

	Value for:			
Type of value for Phase IA	**Fecal coliform (CFU/100 mL) in influent**	**Fecal coliform (CFU/100 mL) in effluent**	**Fecal coliphage (PFU/100 mL) in influent**	**Fecal coliphage (PFU/100 mL) in effluent**
Minimum value	3.9×10^6	<1	4.0×10^5	<1
Maximum value	8.0×10^6	8	6.0×10^5	<1
Avg. value	5.7×10^6	1.25	5.1×10^5	<1

Alkalinity. Influent and effluent alkalinity data are shown in Figure 3.55. The data indicate that the raw wastewater feed contained 80 to 100 mg of alkalinity/L. The data indicate that alkalinity was sufficient in the raw wastewater and that there was 25 to 65 mg of alkalinity/L remaining in the MBR permeate.

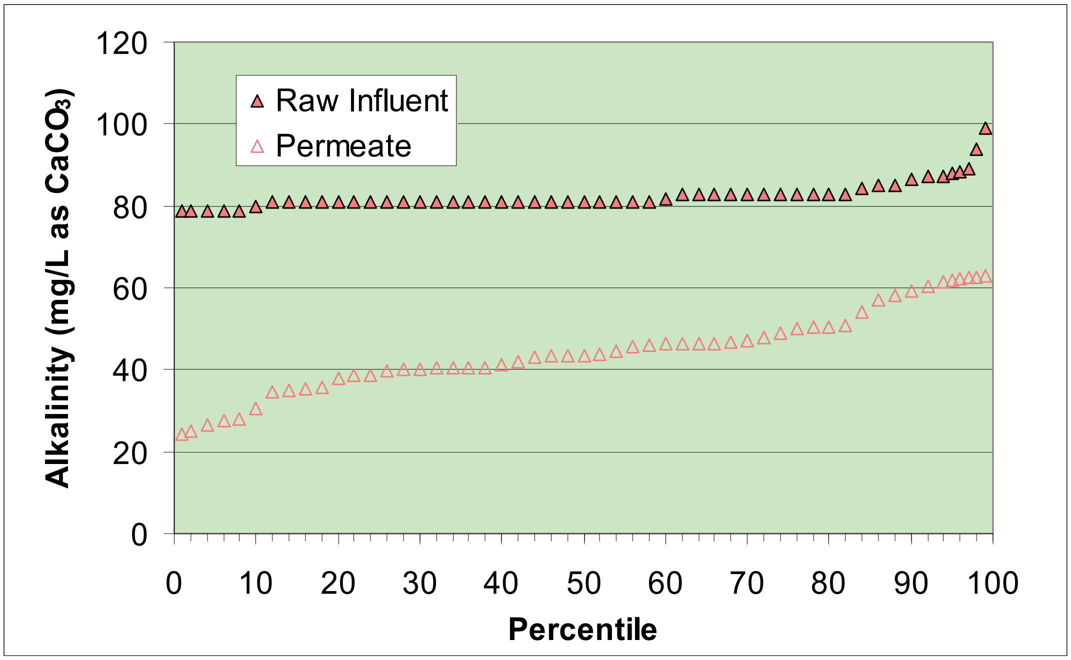

Figure 3.55. Influent and effluent (permeate) alkalinity data for Koch MBR (raw wastewater).

Overall average water quality and removal efficiencies. Table 3.3 (above) gives the overall average values of influent and effluent for all the water quality parameters discussed above. Table 3.3 also shows the average removal efficiencies for the same parameters where appropriate.

3.2.2 Centrate Feed

The goal of Phase IB was to demonstrate the utility of the MBR technology for treatment of a high-strength centrate waste stream. This phase of the pilot study was conducted from April 29, 2004, to July 29, 2004 (3 months). The pilot MBRs were operated nearly continuously during this period, except for short shutdowns (1 or 2 days) caused by power failures, equipment failures, and needed cleanings. Five MBRs were available for this portion of the study (Enviroquip, Huber, Ionics, US Filter, and Zenon). The Koch MBR was not yet on site during this phase and was never evaluated on centrate feed in this study. The CCH currently utilizes a Zimpro sludge heat stabilization process at its two largest treatment plants (Honouliuli [26 MGD] and Sand Island [75 MGD]) to stabilize primary sludge by cooking it at 325 °F and 250 psi. The heat-stabilized sludge is dewatered in centrifuges, and the high-strength centrate is recycled to the head of the treatment plant. This recycling stream is responsible for approximately 10% of the mass of BOD discharged from these treatment plants and the source of most of the color. The city was interested in determining the feasibility of treating the centrate in a small footprint in order to essentially gain a 10% capacity increase and to reduce the color in the secondary effluent prior to tertiary treatment for recycling. Preliminary analyses of the centrate stream found BOD_5 values between 3200 and 4520 mg/L, TSS values between 1250 and 3740 mg/L, and color units between 2240 and 4100. The treatment goal was to reduce color to 20 color units. Based on the preliminary data, the waste strength was well in excess of the aeration capacity of the MBR pilot units at their rated fluxes. Therefore, the centrate was diluted approximately in a ratio of 10:1 with tertiary effluent (recycled water from the Honouliuli Water Recycling Facility) to reduce the organic loading and the operating fluxes of the MBR pilots were de-rated by approximately 50% to increase retention time under aeration. A 3-mm-pore-size fine screen was used for pretreatment of the centrate in this phase, and due to the nature of the waste, there were virtually no screenings collected. There were no nutrient removal goals, and no attempt was made to optimize pilot MBR operations for nutrient removal. The data are divided into process operating data and water quality data. The process operating data include flux, TMP, MLSSs, and DO concentrations. The water quality data include influent and effluent BOD_5, TOC, TSS, total-N, ammonia-N, nitrate-N, total-P, orthophosphorus, color, turbidity, UVT_{254}, alkalinity, O&G, TDS, fecal coliform, and fecal coliphage. COD was not measured during Phase IB.

3.2.2.1 Process Operating Data

The MBRs were operated at one-half their design fluxes during Phase IB (Enviroquip, 7 GFD; Huber, 8.5 GFD; and Ionics, US Filter, and Zenon, 5 GFD). None of the MBR pilots was cleaned during Phase IB. The MBR pilot units were operated at an MLSS between 4000 and 20,000 mg/L in Phase IB (see Figure 3.56). It was observed that, when the MLSS was very high, the pilot units were limited in DO (see Figure 3.57).

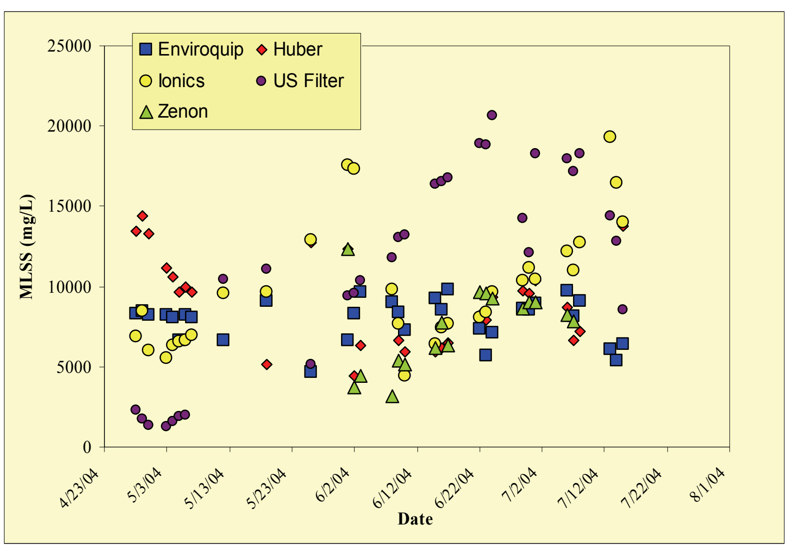

Figure 3.56. MLSSs during Phase IB (centrate).

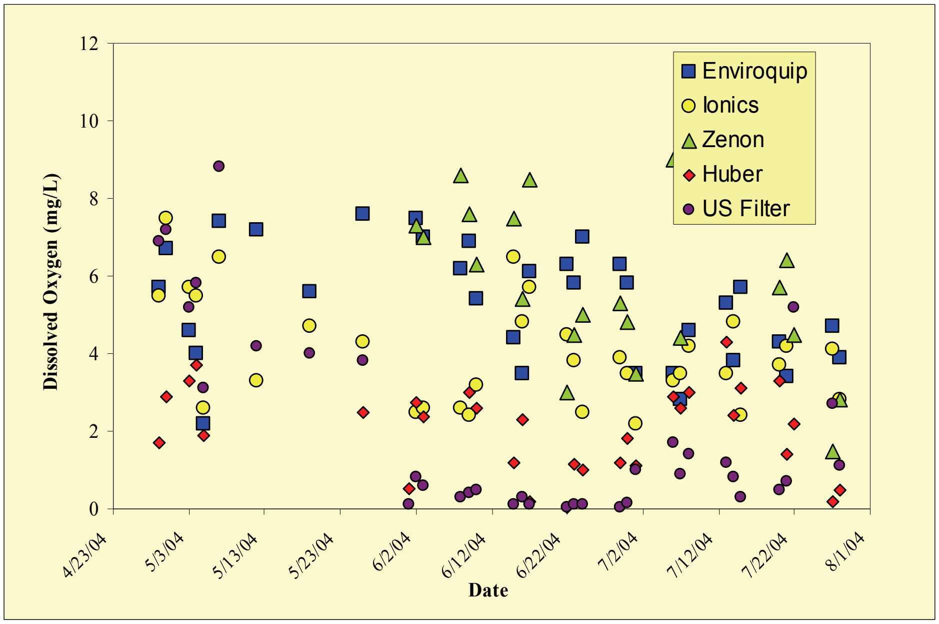

Figure 3.57. Mixed liquor DO during Phase IB (centrate).

3.2.2.2 Water Quality Data

The water quality data are presented in Figures 3.58 through 3.77 and Tables 3.5 through 3.7. Overall, the effluent (permeate) water quality produced by each of the MBRs was quite good in many respects; however, the MBRs were generally unable to remove the brownness from the centrate, which proved to be recalcitrant organic matter consisting of either dissolved substances and/or a very fine suspension of colloidal matter. The centrate feed was found to be somewhat corrosive and generally hard on the membrane process equipment (pumps and seals) and membrane material (fouling). Overall average influent and effluent values and overall removal efficiencies for all of the water quality parameters analyzed are reported at the end of this section. In general, it would appear that MBRs may not be the best process for treatment of this type of waste even with pretreatment to reduce organic strength by 90%.

BOD. Influent and effluent BOD_5 data are shown in Figures 3.58 and 3.59, respectively. The data indicate that the centrate feed was of higher strength than the raw wastewater and that the BOD_5 varied between approximately 125 and 425 mg/L. In addition, approximately 80% of the data fall between 225 and 550 mg/L. Figure 3.59 shows that very low values of effluent BOD_5 were still achieved by the MBR systems. The figure indicates that greater than 90% of the BOD_5 values are less than 7 mg/L for each of the MBRs and that the performances of the five different types of MBRs are slightly different but are all quite good. It appears that the US Filter and Huber units had slightly higher permeate BOD concentrations than did the other three units, which were very similar.

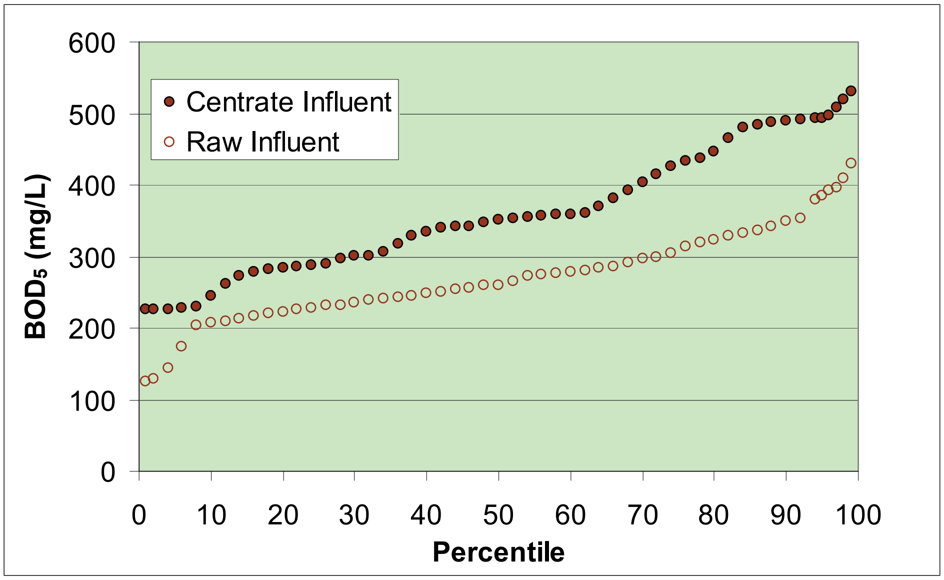

Figure 3.58. Heat-treated centrate influent BOD_5 concentration distribution during Phase IB.

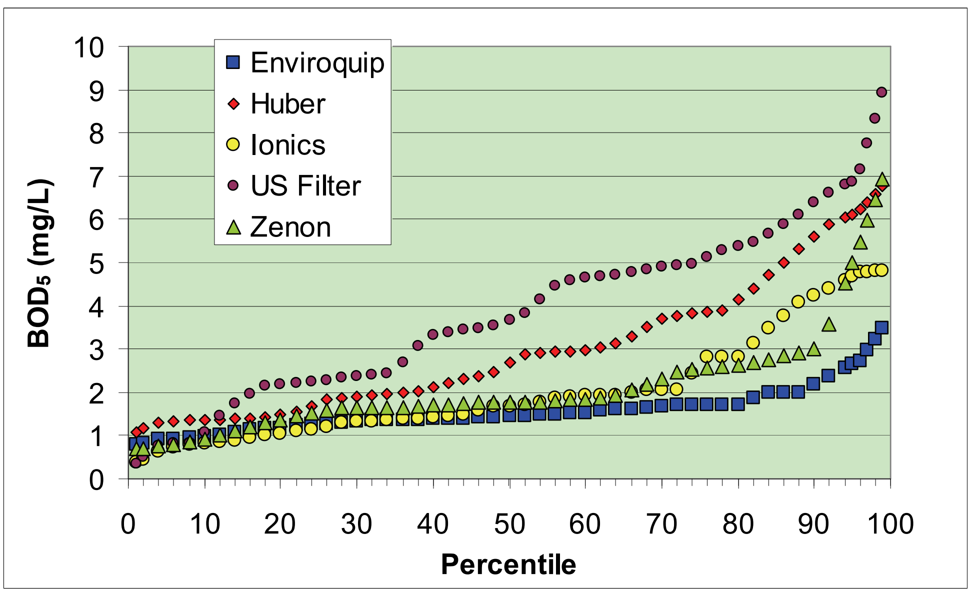

Figure 3.59. Effluent (permeate) BOD_5 concentration distributions during Phase IB (centrate).

TOC. Influent and effluent TOC data are shown in Figures 3.60 and 3.61, respectively. The data indicate that centrate feed TOC concentrations were approximately 100 mg/L greater than those for raw wastewater. Figure 3.61 shows that the MBR permeates contained greater amounts of presumably recalcitrant organic carbon than during Phase IA. Figure 3.61 indicates that permeate TOC concentrations increased by 10 to 20 mg/L across the whole distribution. The permeate TOC is most likely indicative of additional SMP present in the centrate waste stream (the centrate results from a heat-treated sludge process that lyses all bacterial cells). This additional SMP and/or fine organic colloidal material was responsible for enhanced fouling rates in this phase. Figure 3.61 seems to show differences between the MBRs with somewhat higher concentrations of TOC passing through the US Filter unit (about 70% of values are > 25 mg/L, versus less than 20% being > 25 mg/L for Huber and Zenon and less than 10% being > 25 mg/L for Enviroquip and Ionics).

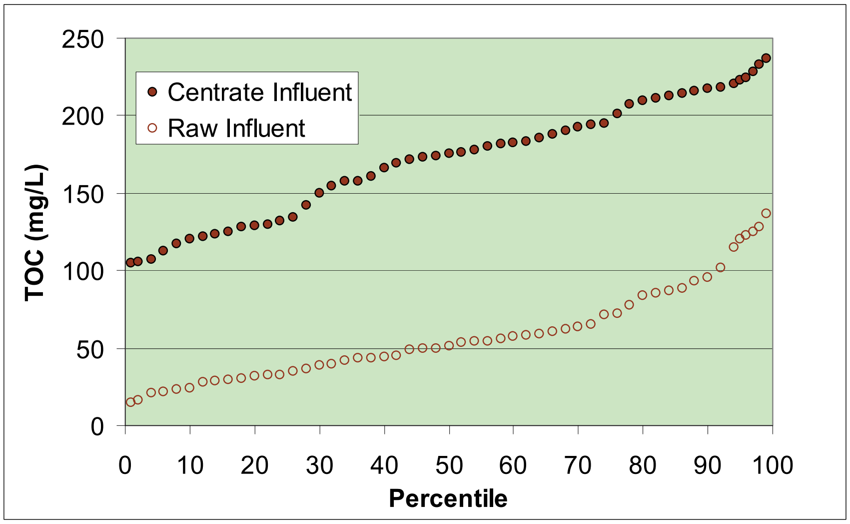

Figure 3.60. Centrate influent TOC concentration distribution during Phase IB.

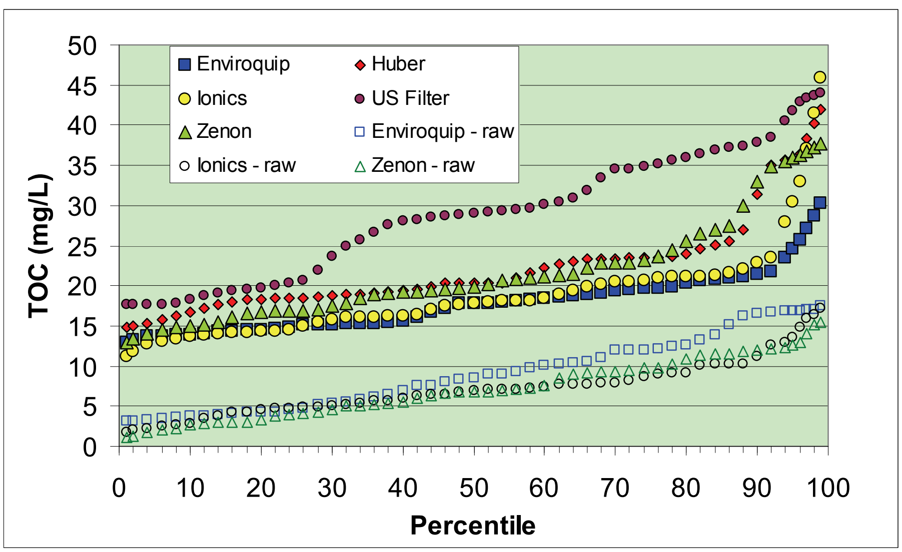

Figure 3.61. Effluent TOC concentration distributions during Phase IB (centrate).

TSS. Influent and effluent TSS data are shown in Figures 3.62 and 3.63, respectively. The data indicate that the centrate feed had strength similar to that of the raw wastewater in Phase

IA. Figure 3.63 shows that the MBRs were able to maintain very low permeate TSS concentrations that are typical for MBR systems. The figure indicates that greater than 90% of the TSS values are less than 5 mg/L for each of the MBRs and that the performances of the five different types of MBRs are comparable.

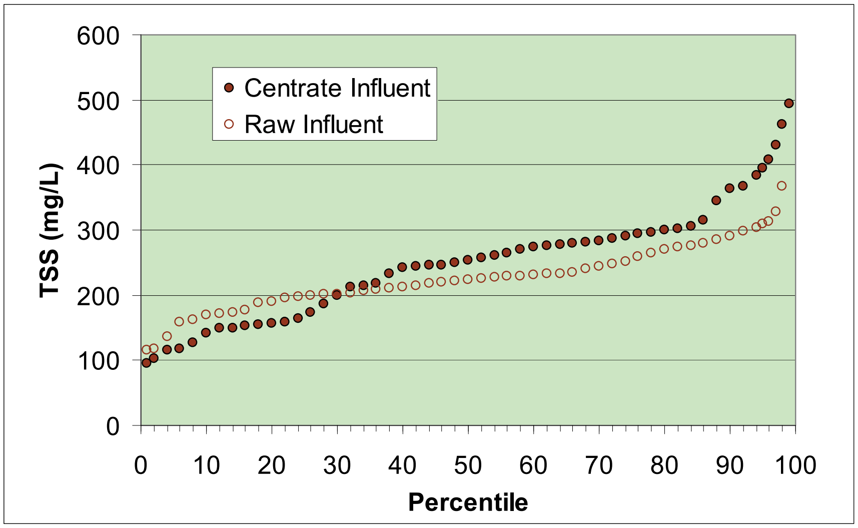

Figure 3.62. Centrate influent TSS concentration distribution during Phase IB.

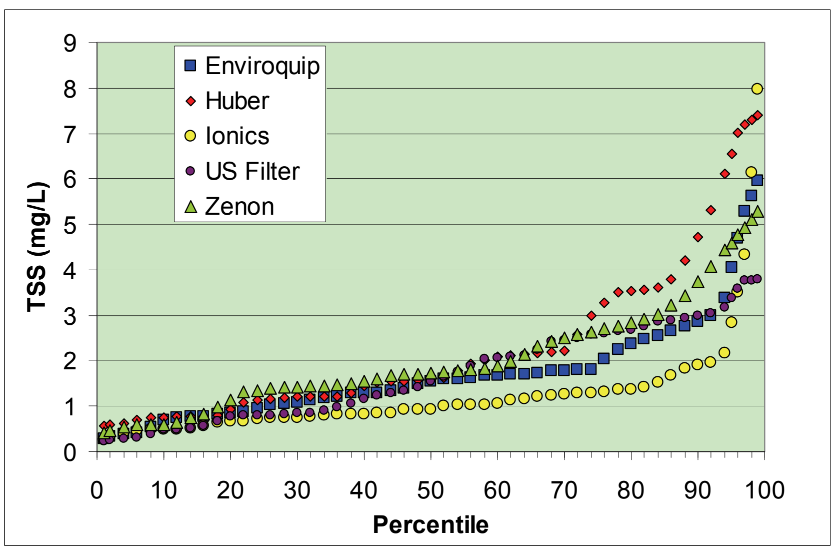

Figure 3.63. Effluent (permeate) TSS concentration distributions during Phase IB (centrate).

Nitrogen species. Influent, effluent, and removal efficiency data for total nitrogen are shown in Figures 3.64, 3.65, and 3.66, respectively. Influent ammonia, effluent ammonia, and effluent nitrate data are shown in Figures 3.67, 3.68, and 3.69, respectively. The data indicate that the centrate feed contained considerably more total nitrogen than did the raw wastewater and varied between approximately 35 and 85 mg/L. Ammonia nitrogen varied from 25 to 50 mg/L. Figure 3.65 indicates that the amount of total nitrogen remaining in the effluent varied from 5 to almost 55 mg/L. All of the MBR pilots except Huber are equipped with anoxic zones and mixed liquor recycling systems. However, the degree of nitrogen removal is dependent upon achievement of nitrification prior to denitrification. At various times there was insufficient DO present in the MBRs (due to high TSS concentrations) to allow complete nitrification, and under these conditions, denitrification-based nitrogen removal was reduced. This finding can be observed in Figures 3.68 and 3.69, which show that complete nitrification was achieved between 50 and 95% of the time during Phase IB in the different MBRs. From Figure 3.69, it can be observed that the Huber unit achieved less denitrification than did most of the other units because it was operated without an anoxic zone.

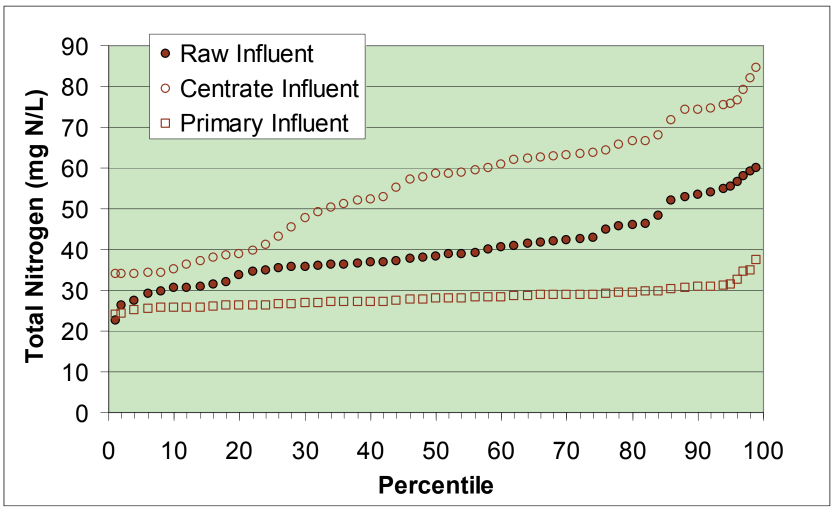

Figure 3.64. Centrate influent total nitrogen concentration distribution during Phase IB.

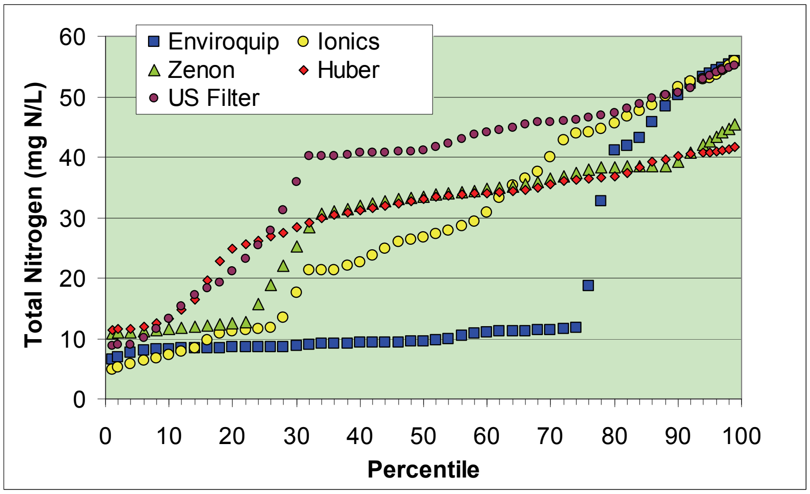

Figure 3.65. Effluent (permeate) total nitrogen concentration distributions during Phase IB (centrate).

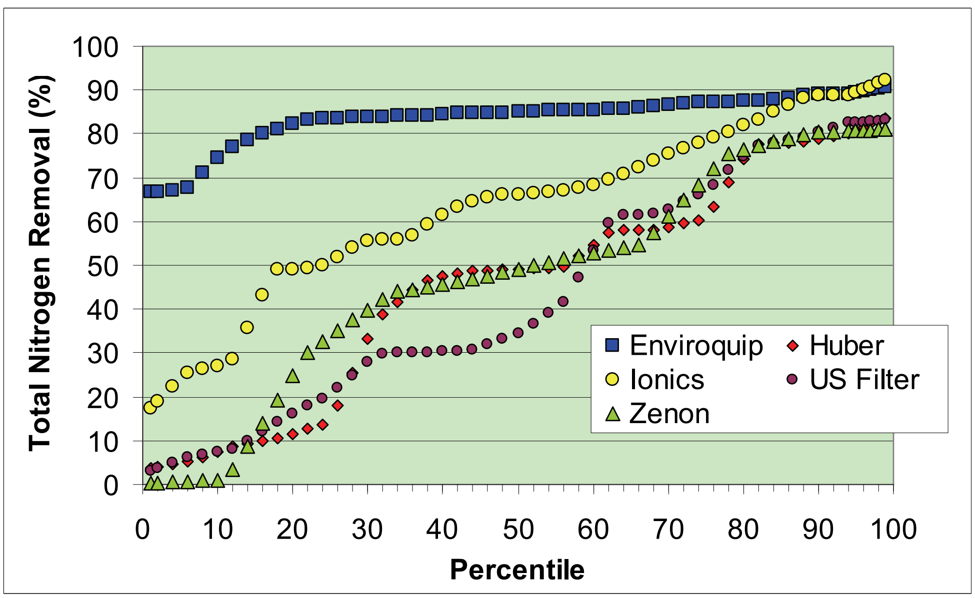

Figure 3.66. Total nitrogen removal efficiency distributions during Phase IB (centrate).

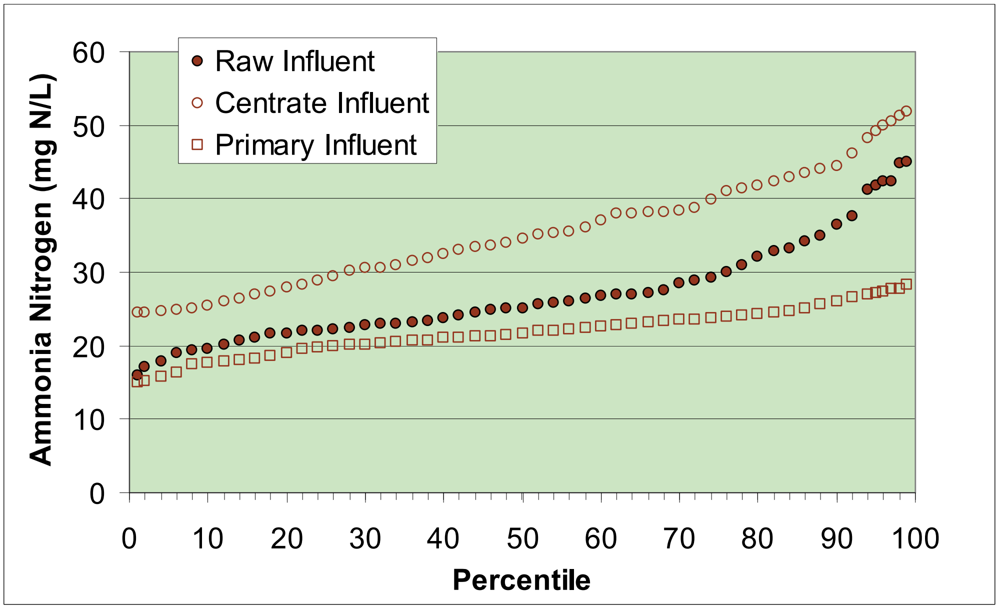

Figure 3.67. Centrate influent ammonia nitrogen distribution during Phase IB (centrate).

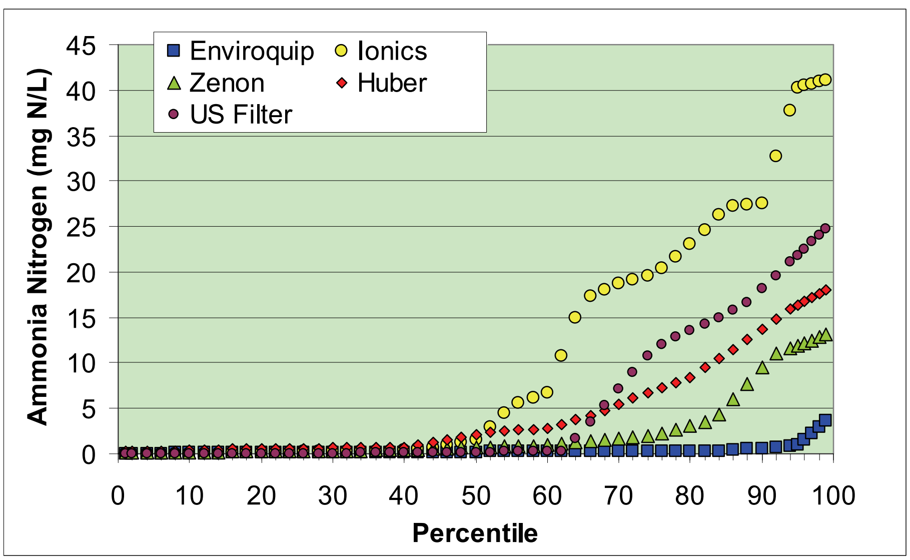

Figure 3.68. Effluent (permeate) ammonia nitrogen distributions during Phase IB (centrate).

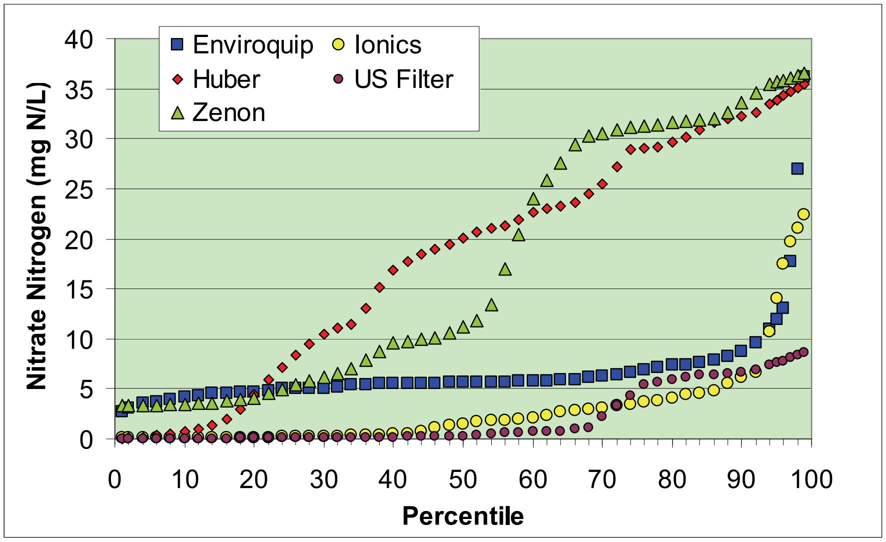

Figure 3.69. Effluent (permeate) nitrate nitrogen distributions during Phase IB (centrate).

Phosphorus species. Influent, effluent, and removal efficiency data for total phosphorus are shown in Figures 3.70, 3.71, and 3.72, respectively. The data indicate that the centrate feed contained between approximately 4 and 15 mg of total phosphorus/L. Figure 3.71 shows that effluent total phosphorus varied from nearly zero to about 6 mg/L. Figure 3.72 indicates that phosphorus removal was significant for each of the MBRs and that differences occurred. Specifically, the US Filter MBR pilot unit achieved very good phosphorus removal (at least 80% removal for 80% of the time). The US Filter unit was the only one that was specifically set up for Bio-P removal. Figure 3.73 indicates that there were slight differences in the amount of orthophosphate in the MBR permeates.

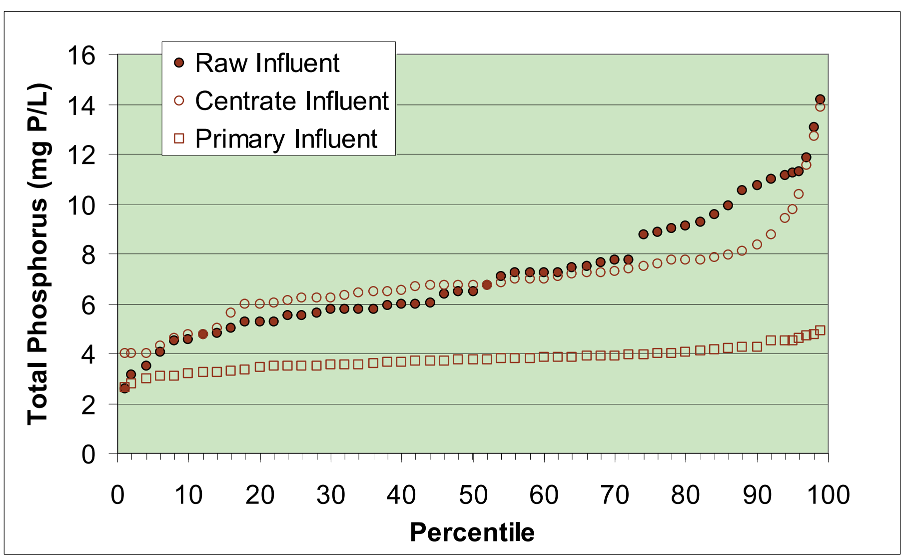

Figure 3.70. Centrate influent total phosphorus concentration distribution during Phase IB.

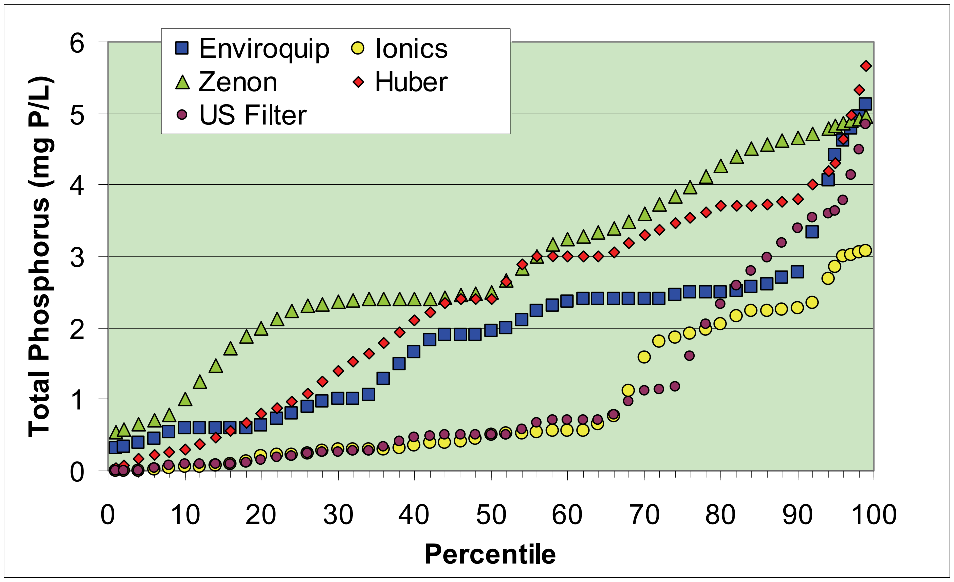

Figure 3.71. Effluent (permeate) total phosphorus distributions during Phase IB (centrate).

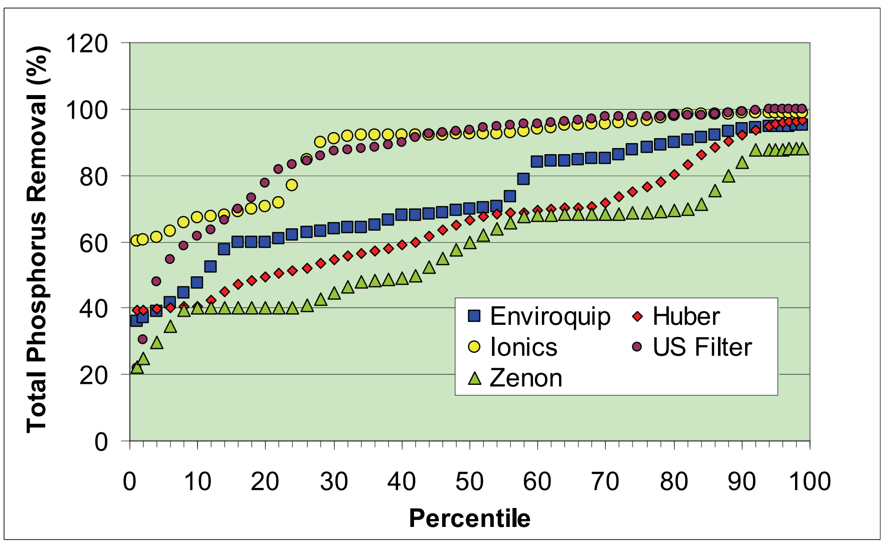

Figure 3.72. Total phosphorus removal efficiency distributions during Phase IB (centrate).

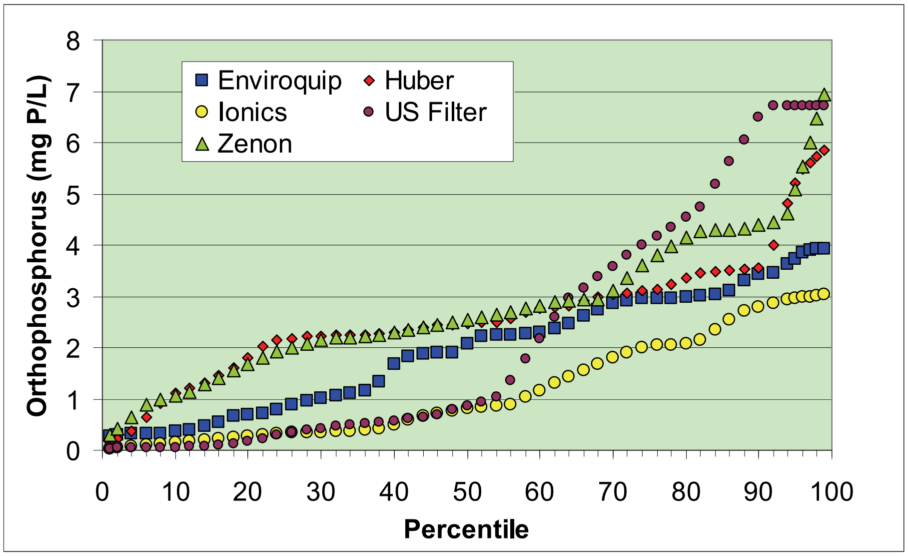

Figure 3.73. Effluent (permeate) orthophosphorus distributions during Phase IB (centrate).

Color. Effluent data for color are shown in Figure 3.74. Color was not measured in the centrate influent. The data indicate that the permeate color varied considerably on a relative scale. T&D has a goal to reduce effluent color to less than 20 Pt-Co units, which is indistinguishable from the value for potable groundwater. It is apparent that the MBRs were not able to meet this goal and color values ranged from about 100 to over 300. In this phase, the permeate took on a distinct brownness. Figure 3.74 indicates that the performances of the five different types of MBRs are generally comparable, with the Enviroquip unit producing slightly lower color values and the US Filter unit producing somewhat higher color values than the other MBRs.

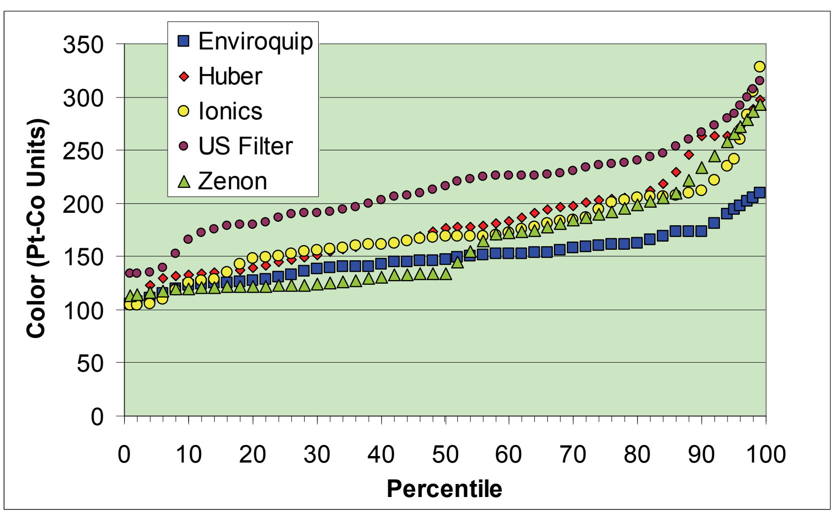

Figure 3.74. Effluent (permeate) color value distributions during Phase IB (centrate).

Turbidity. Effluent data for turbidity are shown in Figure 3.75. No reliable data were obtained for the Huber, US Filter, or Zenon MBR pilot units during this phase. The data indicate that the intense color that passed through the membranes was also measured at least partly as turbidity, suggesting a fine particulate fraction.

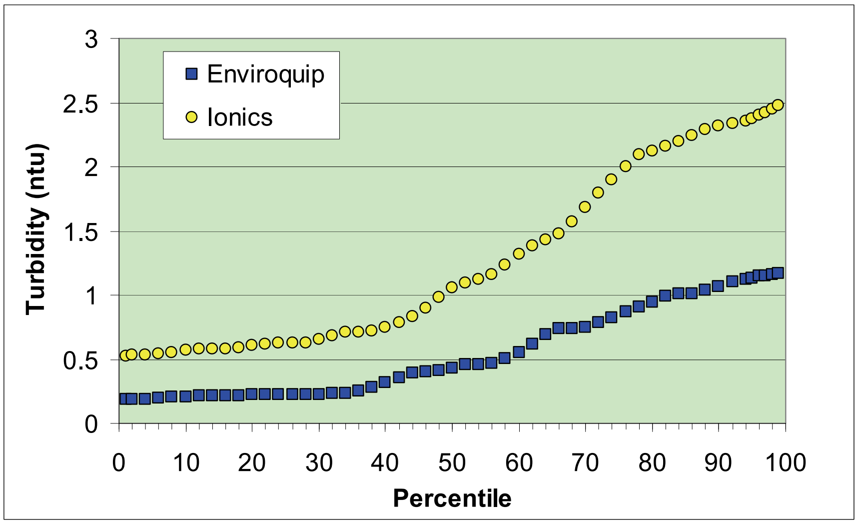

Figure 3.75. Effluent (permeate) turbidity distributions during Phase IB (centrate).

UVT. Influent and effluent UVT_{254} data are shown in Figures 3.76 and 3.77, respectively. The data indicate that the raw wastewater feed had an extremely low UVT of between 1 and 5%, indicating a large quantity of UV-absorbing material. Figure 3.77 shows that the permeate UVTs are larger than the influent UVTs; however, they are still only between 10 and 30% (similar to raw wastewater). The performances of each of the five different types of MBRs are quite comparable, except that the US Filter permeate had somewhat lower UVTs than did the other MBRs, indicating greater color (see Figure 3.74).

O&G. No O&G data were collected during Phase IB.

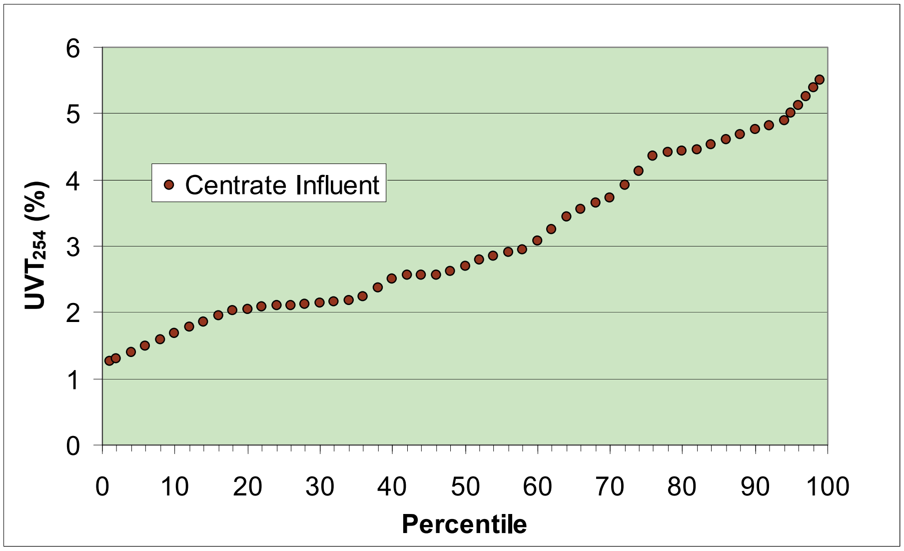

Figure 3.76. Raw influent UVT_{254} distribution during Phase IB.

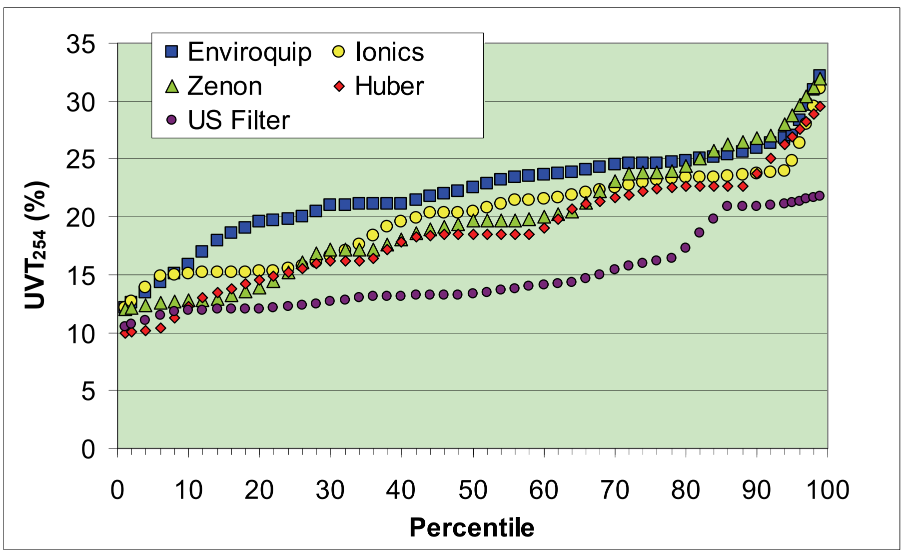

Figure 3.77. Effluent (permeate) UVT_{254} distributions during Phase IB (centrate).

Fecal coliform and coliphage. Fecal coliform and coliphage were not detected in the effluent from the MBRs, with the exception of only a few events for coliform, which were subsequently attributed to sample contamination at the pilot site. Minimum, maximum, and average values for the influent are shown in Table 3.5. The values in Table 3.5 are approximately 1 order of magnitude lower than those for raw wastewater (Table 3.1).

Table 3.5. Influent and effluent fecal coliform and coliphage during Phase IB (centrate)

Type of value for Phase IB	Value for:			
	Fecal coliform (CFU/100 mL) in influent	**Fecal coliform (CFU/100 mL) in effluent (all)**	**Fecal coliphage (PFU/100 mL) in influent**	**Fecal coliphage (PFU/100 mL) in effluent**
Minimum value	9.0×10^5	<1	2.2×10^5	<1
Maximum value	1.3×10^7	4	4.9×10^5	<1
Avg. value	5.7×10^6	<1	3.5×10^5	<1

Alkalinity. Alkalinity was measured approximately monthly. Table 3.6 shows the alkalinity data collected during Phase IB. The data indicate that alkalinity was sufficient in the centrate feed and that there was alkalinity remaining in the MBR permeates.

Table 3.6. Influent and effluent alkalinity data for Phase IB (centrate)

Date (mo-day-yr)	Concn (mg/L) of $CaCO_3$ in					
	Influent	**Enviroquip effluent**	**Huber effluent**	**Ionics effluent**	**US Filter effluent**	**Zenon effluent**
4-29-04	191	97	126	82	224	NA
5-5-04	193	108	80	44	97	NA
6-10-04	239	106	66	159	168	97
7-20-04	230	97	70	221	319	93
Avg.	213	102	86	127	202	95

Overall average water quality and removal efficiencies. Table 3.7 gives the overall average values of influent and effluent for all the water quality parameters discussed above. Table 3.7 also shows the average removal efficiencies for the same parameters where appropriate.

Table 3.7. Average water quality data and removal efficiencies during Phase IB (centrate)

	Value for:					
Analyte	**Influent**	**Enviroquip**	**Huber**	**Ionics**	**US Filter**	**Zenon**
BOD_5 (mg/L)	360	1.6 (99.6%)	3.0 (99.2%)	2.0 (99.4%)	3.9 (98.9%)	2.3 (99.4%)
TSS (mg/L)	290	1.7 (99.3%)	2.3 (99.1%)	1.4 (99.5%)	1.7 (99.3%)	2.1 (99.2%)
TOC (mg/L)	171	18 (90%)	22 (87%)	19 (89%)	29 (83%)	22 (87%)
O&G (mg/L)	NA	NA	NA	NA	NA	NA
Nitrogen, Total (mg of N/L)	55.7	18.9 (66%)	30.2 (46%)	28.5 (49%)	37.0 (34%)	29.1 (48%)
Ammonia (mg of N/L)	35.3	0.4	4.7	11.0	6.0	2.7
Nitrate (mg of N/L)	NA	7.3	18.0	3.2	2.2	17.5
Phosphorus, total (mg P/L)	7.0	1.9 (73%)	2.4 (66%)	1.0 (86%)	1.2 (83%)	2.9 (59%)
Orthophosphorus (mg of P/L)	NA	1.9	2.4	1.2	1.3	2.8
Color (Pt-Co)	NA	149	182	176	214	165
UVT_{254} (%)	3.1	22.1	18.6	20.0	14.8	19.9
Turbidity (NTU)	NA	0.55	NA	1.3	NA	NA
Fecal coliform (CFU/100 mL)	5.7×10^6					
Coliphage (PFU/100 mL)	3.5×10^5					
Alkalinity (mg of $CaCO_3$/L)	213	102	86	127	202	95

3.2.3 Primary Effluent Feed

The goal of Phase IC was to demonstrate the utility of the MBR technology for treatment of primary effluent wastewater. The CCH was interested in the treatment of primary effluent wastewater for applications such as treatment plant expansion and treatment plant upgrades for water recycling or nutrient removal. This phase of the pilot study was conducted from August 15, 2004, to January 31, 2005 (5 months). Five MBRs were available at the start of this portion of the study (Enviroquip, Huber, Ionics, US Filter, and Zenon). The Koch MBR was not yet on site during this phase and was never evaluated on primary effluent in this study. The pilot MBRs were operated nearly continuously during this period, except for short shutdowns (1or 2 days) caused by power failures, equipment failures, and needed cleanings. The Zenon pilot unit was decommissioned and moved to the SBWWTP (approximately 10 mi from Honouliuli) on October 22, 2004. The US Filter unit became inoperable (transformer failure) on November 24, 2004, and was never repaired by the vendor. A 3-mm-pore-size fine screen was used for pretreatment of primary effluent wastewater in this phase, and due to the nature of the waste (screened, degritted, and settled), very few screenings were collected. The main water quality goals were to reduce BOD and TSS to less than 5 mg/L, keep turbidity to less than 0.2 NTU, have UVT greater than 65%, and have a fecal coliform level of less than 1 CFU/100 mL. There were no nutrient removal goals, and no attempt was made to optimize pilot MBR operations for nutrient removal. The data are divided into process operating data and water quality data. The process operating data include flux, TMP, mixed liquor suspended solids, and DO concentrations. The water quality data include influent and effluent BOD_5, TOC, TSS, total-N, ammonia-N, nitrate-N, total-P, orthophosphorus, color, turbidity, UVT_{254}, alkalinity, O&G, TDS, fecal coliform, and fecal coliphage. COD was not measured during Phase IC.

3.2.3.1 Process Operating Data

The MBRs were operated at their design fluxes during Phase IC (Enviroquip, 14.7 GFD; Huber, 17.6 GFD; and Ionics, US Filter, and Zenon, 10 GFD). None of the MBR pilots was cleaned during Phase IC. The MBR pilot units were operated at an MLSS between 2000 and 10,000 mg/L in Phase IC (see Figure 3.78). It was observed that, when the MLSS was very high, the pilot units were limited in DO content (see Figure 3.79).

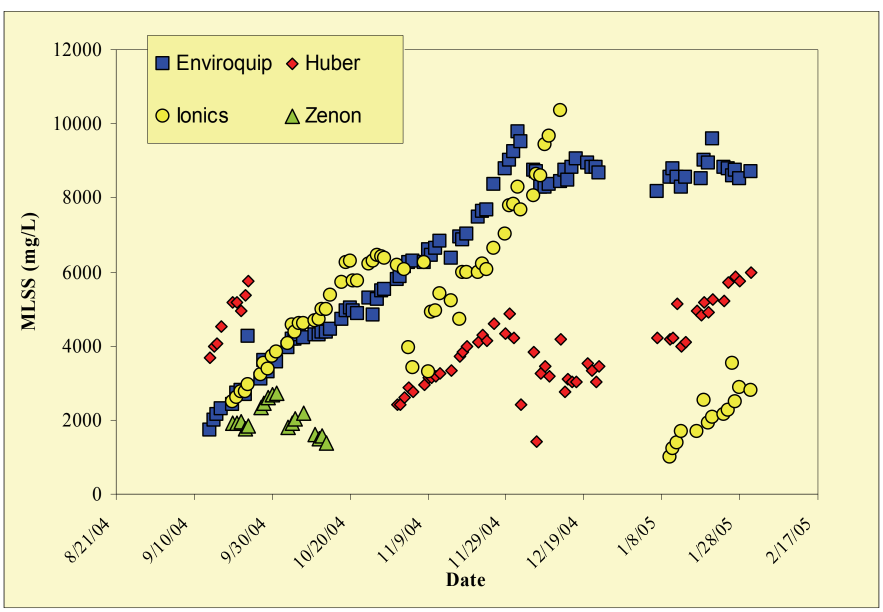

Figure 3.78. MLSSs during Phase IC (primary effluent).

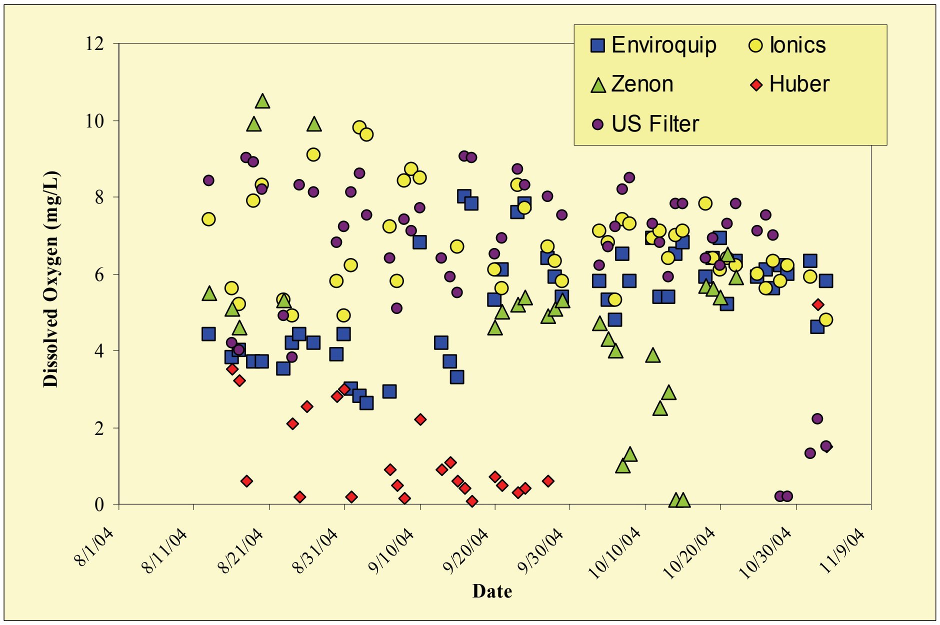

Figure 3.79. Mixed liquor DO during Phase IC (primary effluent).

3.2.3.2 Water Quality Data

The water quality data are presented in Figures 3.80 through 3.101 and Tables 3.8 through 3.10. Overall, the effluent (permeate) water quality produced by each of the MBRs was excellent by industry standards for secondary effluent and/or filtered secondary (tertiary) effluent. Overall average influent and effluent values and overall removal efficiencies for all of the water quality parameters analyzed are reported at the end of this section.

BOD. Influent and permeate BOD_5 data are shown in Figures 3.80 and 3.81, respectively. The data indicate that the primary effluent wastewater feed was of medium strength and that the BOD_5 varied between approximately 100 and 150 mg/L. Figure 3.81 shows the very low values of effluent BOD_5 that are typical for MBR systems. The figure indicates that more than 90% of the BOD_5 values are less than 4 mg/L for each of the MBRs and that the performances of the five different types of MBRs are very comparable. Many of the MBR vendors will guarantee permeate BOD averages of less than 5 mg/L, which is borne out in this data set.

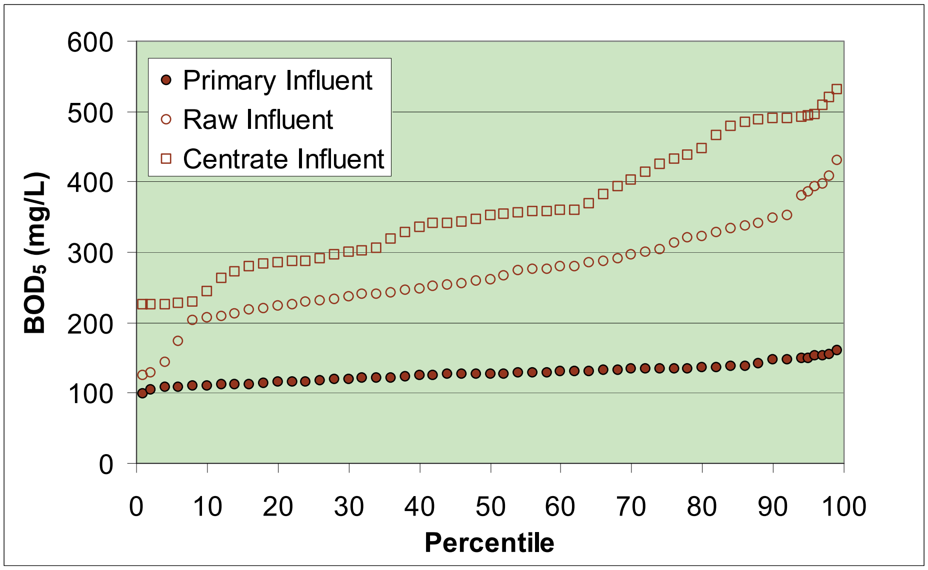

Figure 3.80. Primary effluent feed BOD_5 concentration distribution during Phase IC.

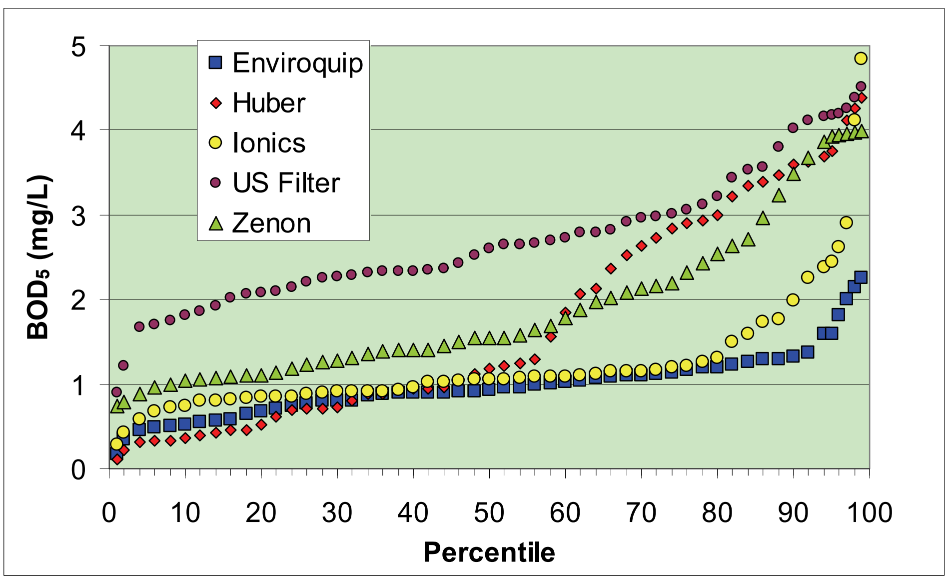

Figure 3.81. Effluent (permeate) BOD_5 distributions during Phase IC (primary effluent).

TOC. Influent and permeate TOC data are shown in Figures 3.82 and 3.83, respectively. The data indicate that the influent TOC varied between approximately 20 and 70 mg/L. Figure 3.83 shows that the MBR permeates contain small yet significant amounts of organic carbon (1 to 18 mg/L). Again, this means that a small amount of SMP that is not readily degradable as BOD_5 passes through the MBR system. Figure 3.83 seems to show some differences between the MBRs, with slightly higher concentrations of TOC passing through the Huber MBR than through the others.

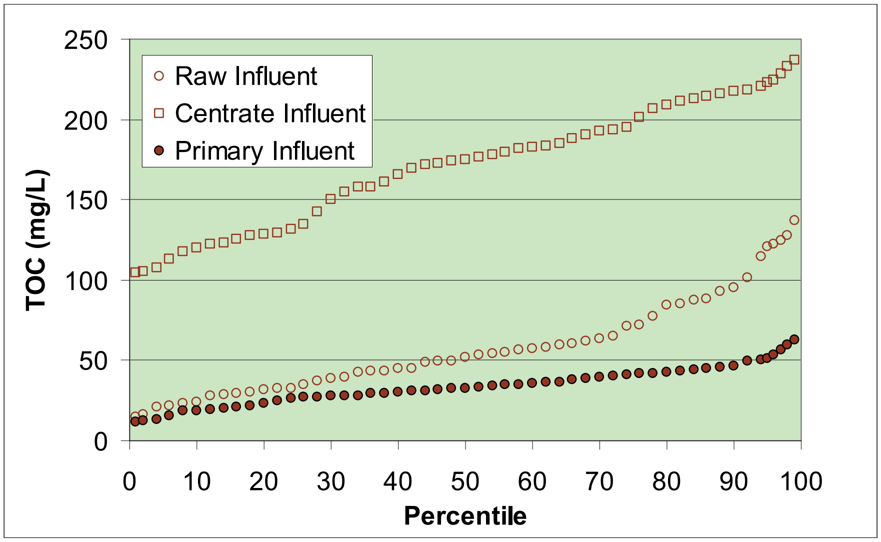

Figure 3.82. Primary effluent feed TOC concentration distribution during Phase IC.

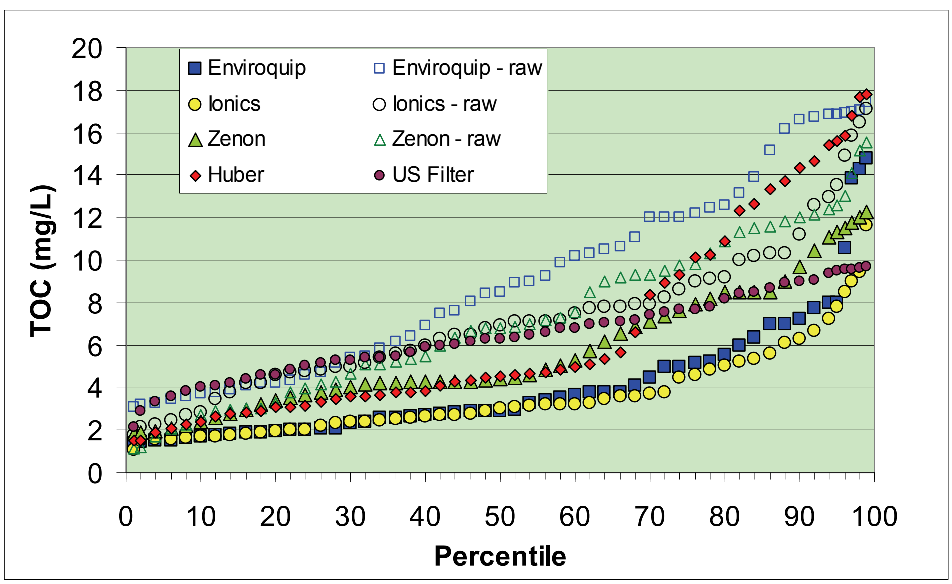

Figure 3.83. Effluent (permeate) TOC distributions during Phase IC (primary effluent).

TSS. Influent and effluent TSS data are shown in Figures 3.84 and 3.85, respectively. The data indicate that the primary effluent feed TSS varied between approximately 50 and 100 mg/L. Figure 3.85 shows the very low values of effluent TSS that are typical for MBR systems. The figure indicates that greater than 90% of the TSS values are less than 4 mg/L for each of the MBRs and that the performances of the five different types of MBRs are very comparable. Many of the MBR vendors will guarantee permeate TSS averages of less than 5 mg/L, which is borne out in this data set.

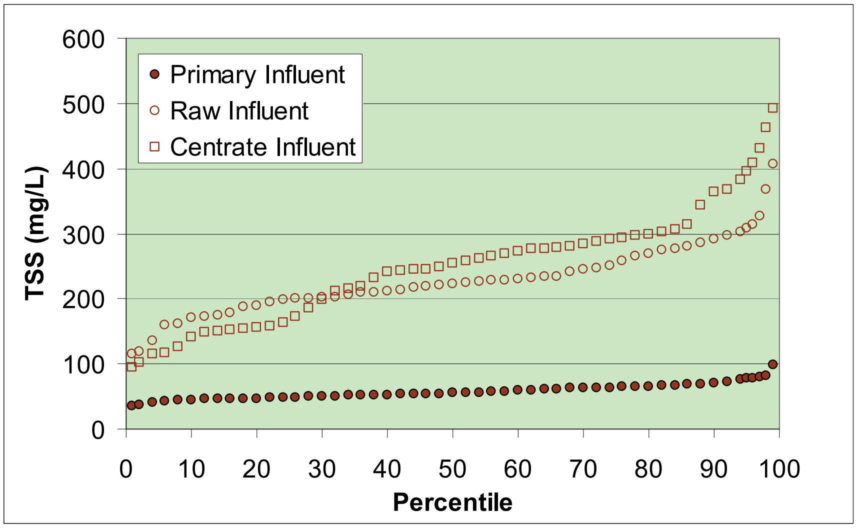

Figure 3.84. Primary effluent feed TSS concentration distribution during Phase IC.

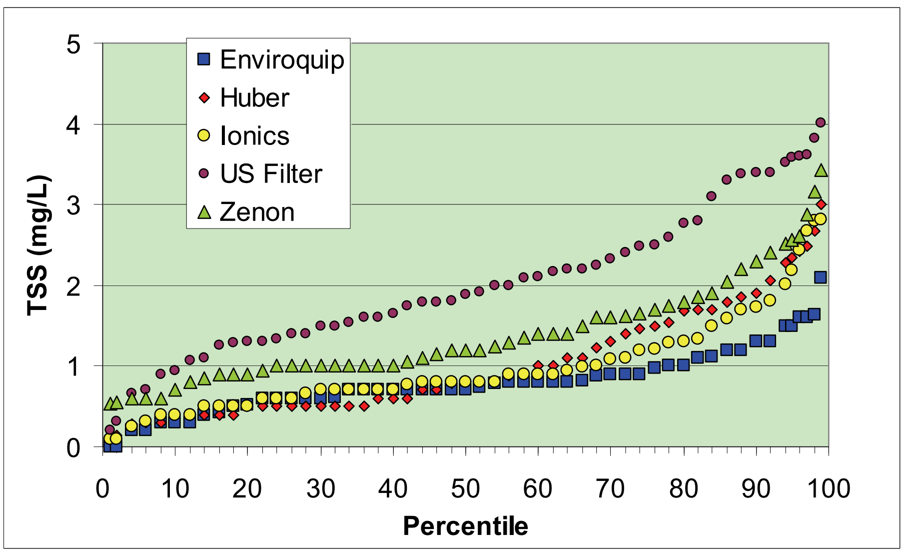

Figure 3.85. Effluent (permeate) TSS distributions during Phase IC (primary effluent).

Nitrogen species. Influent, effluent, and removal efficiency data for total nitrogen are shown in Figures 3.86, 3.87, and 3.88, respectively. Influent ammonia, effluent ammonia, and effluent nitrate data are shown in Figures 3.89, 3.90, and 3.91, respectively. The data indicate that the primary effluent feed contained considerably less total nitrogen than did the raw wastewater and varied between approximately 25 and 40 mg/L. Ammonia nitrogen varied from 15 to 30 mg/L. Figure 3.87 indicates that the amount of total nitrogen remaining in the effluent varied from 5 to almost 30 mg/L. Figures 3.90 and 3.91 show that complete nitrification was achieved between 40 and 95% of the time during Phase IC in the different MBRs.

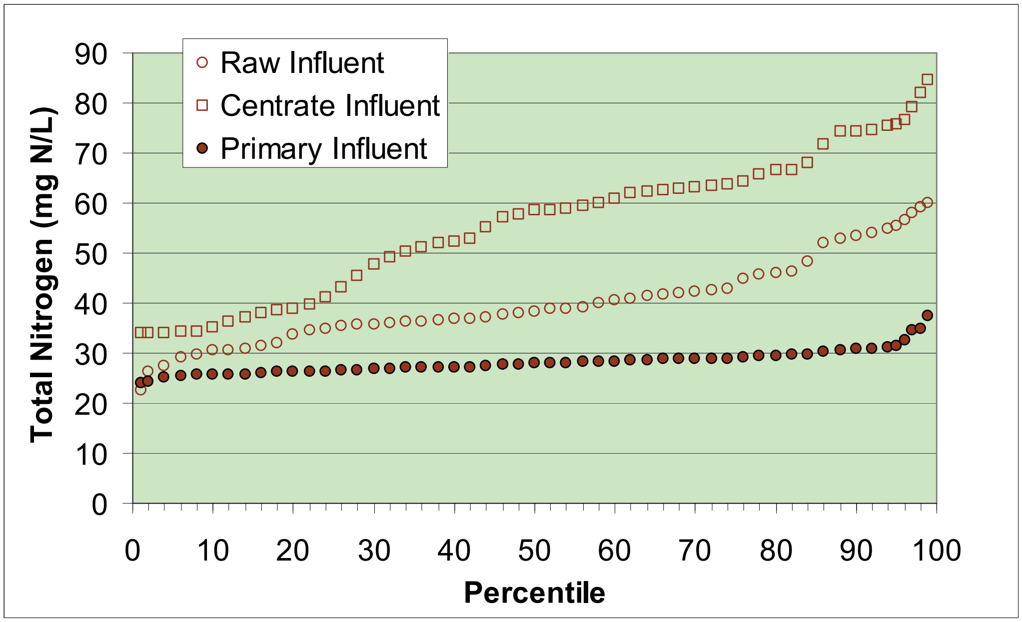

Figure 3.86. Primary effluent feed total nitrogen distribution during Phase IC.

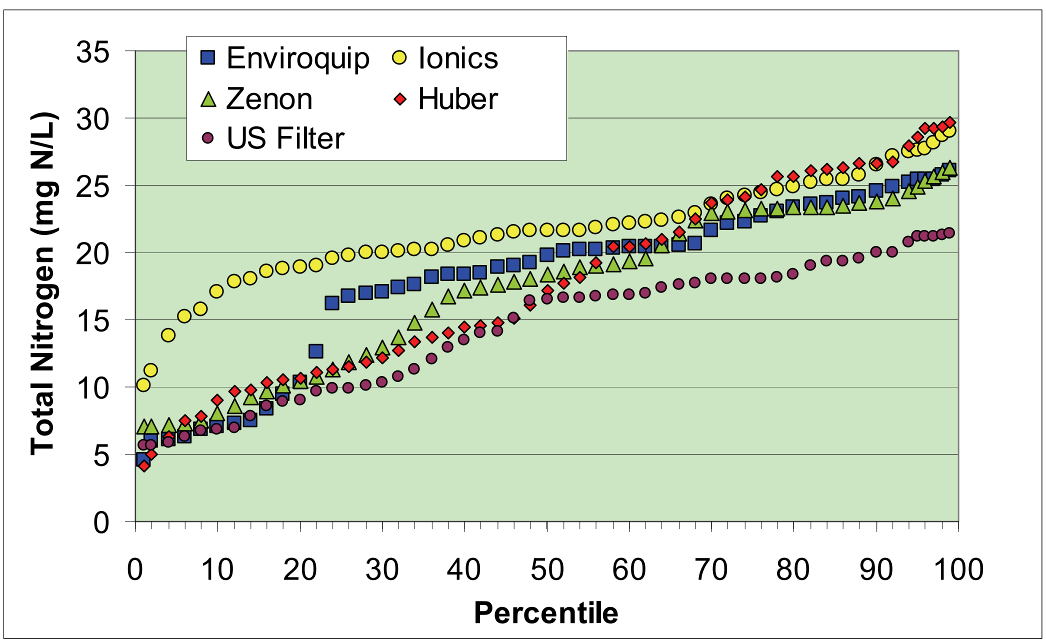

Figure 3.87. Effluent (permeate) total nitrogen distributions during Phase IC (primary effluent).

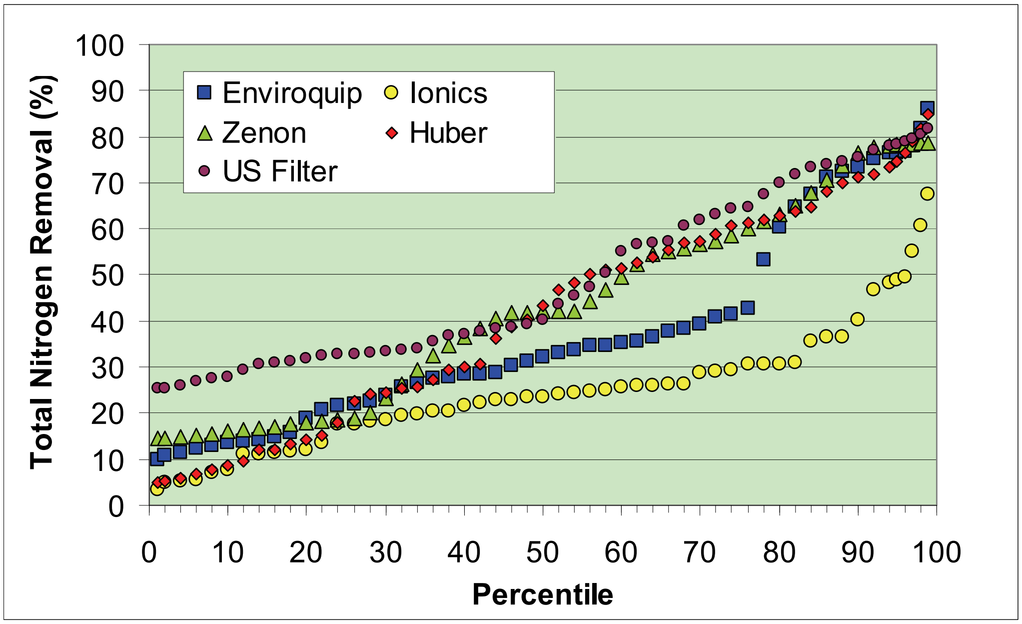

Figure 3.88. Total nitrogen removal efficiency distributions during Phase IC (primary effluent).

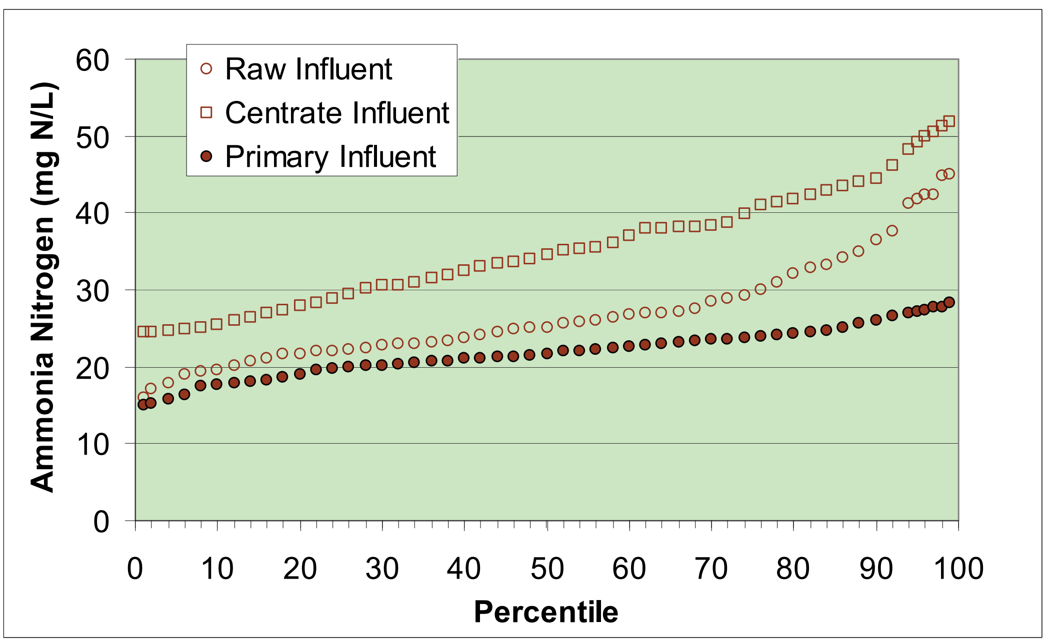

Figure 3.89. Primary effluent feed ammonia nitrogen distribution during Phase IC (primary effluent).

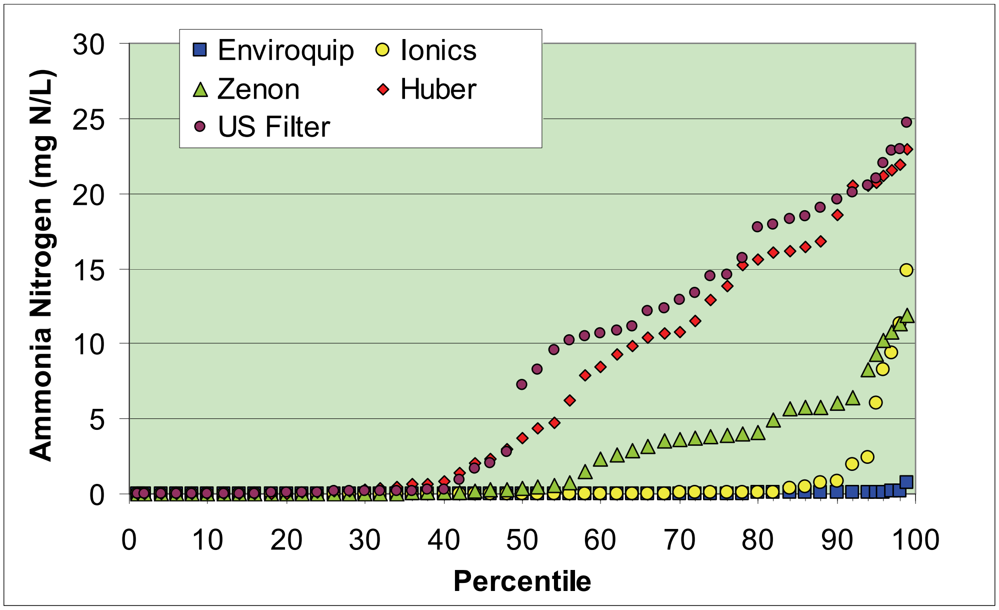

Figure 3.90. Effluent (permeate) ammonia nitrogen distributions during Phase IC (primary effluent).

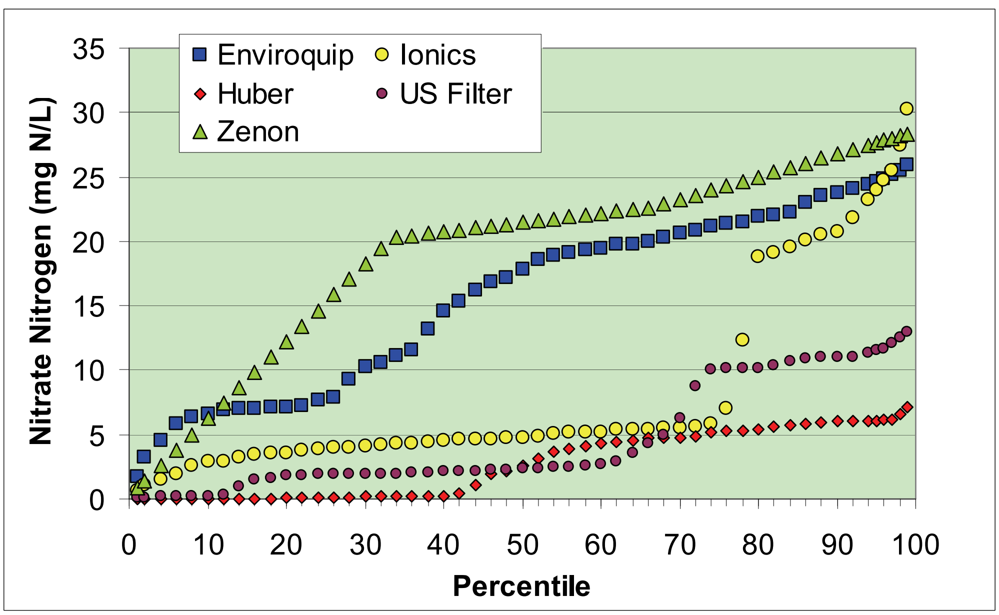

Figure 3.91. Effluent (permeate) nitrate nitrogen distributions during Phase IC (primary effluent).

Phosphorus species. Influent, effluent, and removal efficiency data for total phosphorus are shown in Figures 3.92, 3.93, and 3.94, respectively. The data indicate that the primary effluent feed contained between approximately 3 and 5 mg of total phosphorus/L. Figure 3.93 shows effluent total phosphorus varied from nearly zero to about 4 mg/L. Figure 3.94 indicates that phosphorus removal was not highly significant for each of the MBRs but that differences occurred. Specifically, the US Filter MBR pilot unit achieved the greatest phosphorus removal. The US Filter unit was the only one specifically set up for Bio-P removal. Figure 3.95 indicates that there were slight differences in the amounts of orthophosphate found in the different MBR permeates.

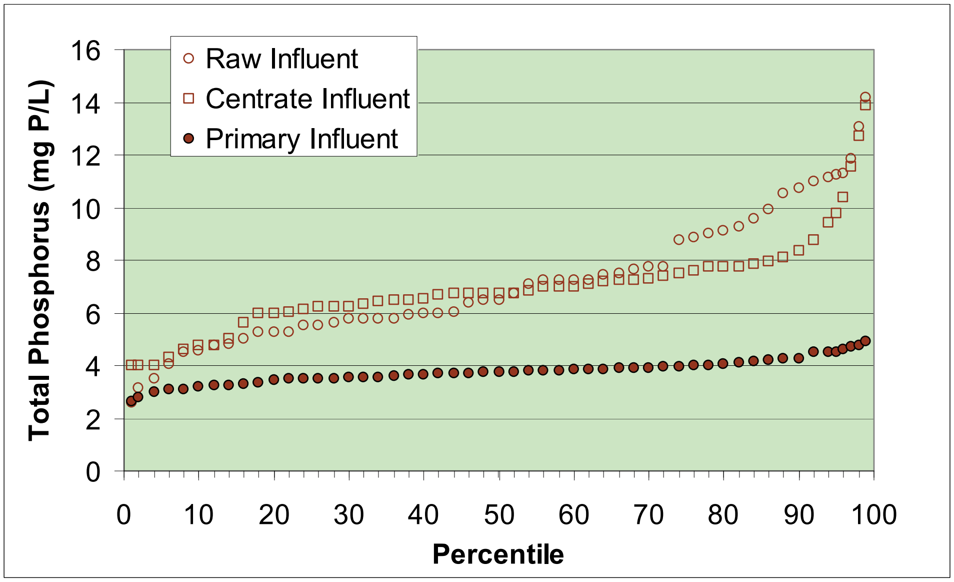

Figure 3.92. Primary effluent feed total phosphorus distribution during Phase IC.

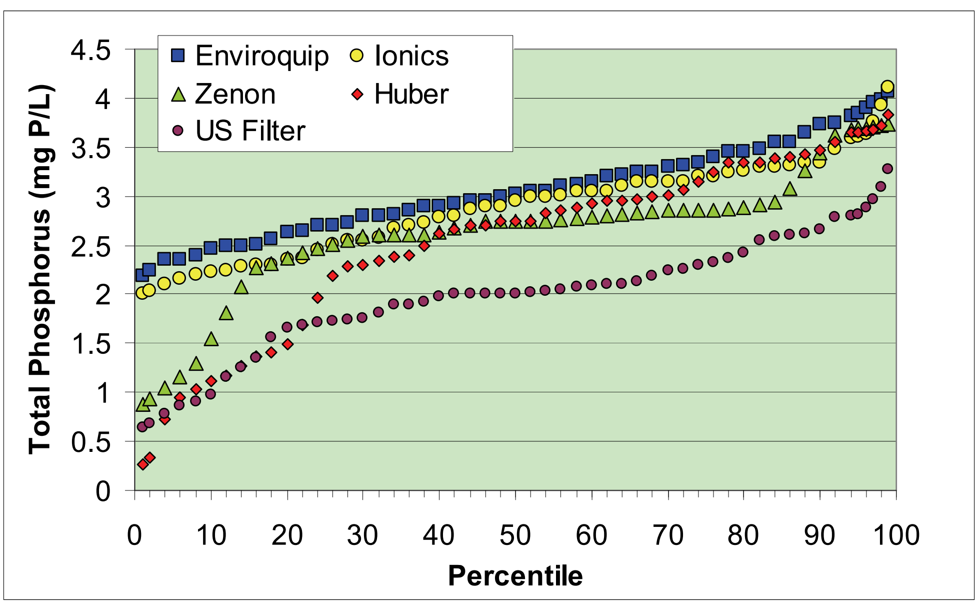

Figure 3.93. Effluent (permeate) total phosphorus distributions during Phase IC (primary effluent).

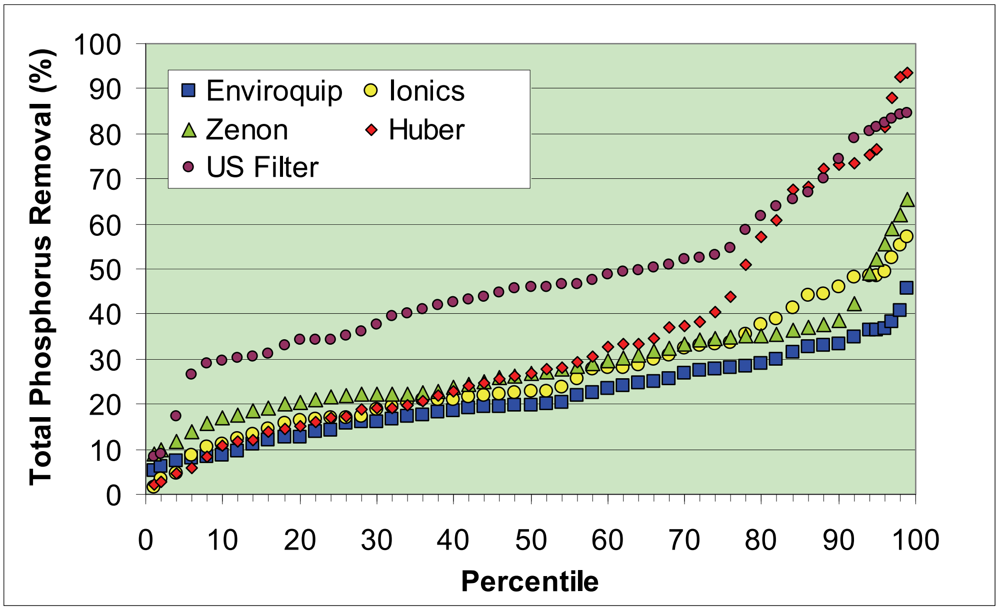

Figure 3.94. Total phosphorus removal efficiency distributions during Phase IC (primary effluent).

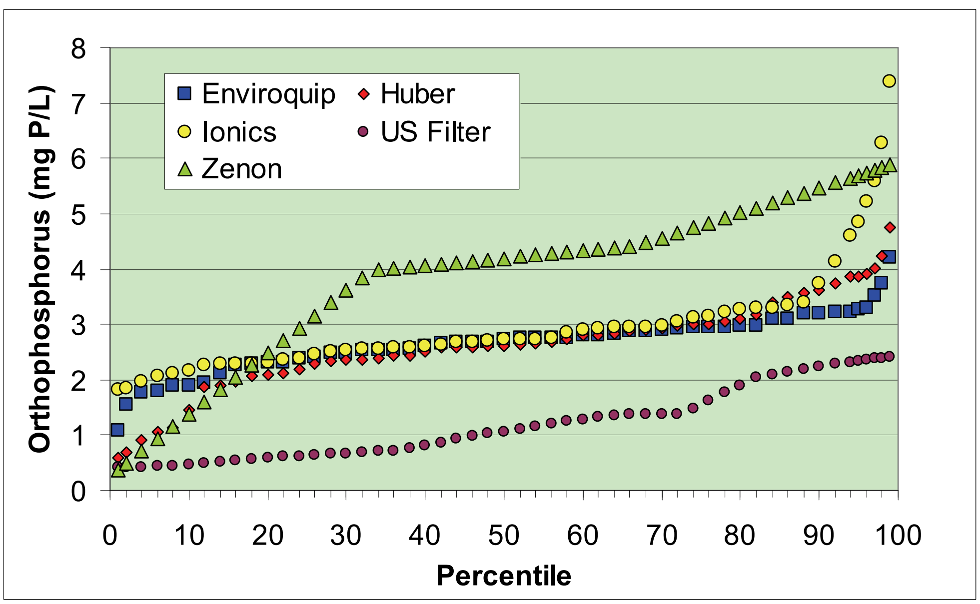

Figure 3.95. Effluent (permeate) orthophosphorus distributions during Phase IC (primary effluent).

Color. Effluent data for color are shown in Figure 3.96. Color was not measured in the primary effluent feed. The data indicate that the permeate color varied considerably on a relative scale. It is apparent that the MBRs were not able to meet the T&D goal of 20 color units and that color values ranged from about 10 to 70. Figure 3.96 indicates that the performances of the five different types of MBRs are generally comparable, with the Huber unit producing slightly higher color values than the other MBRs.

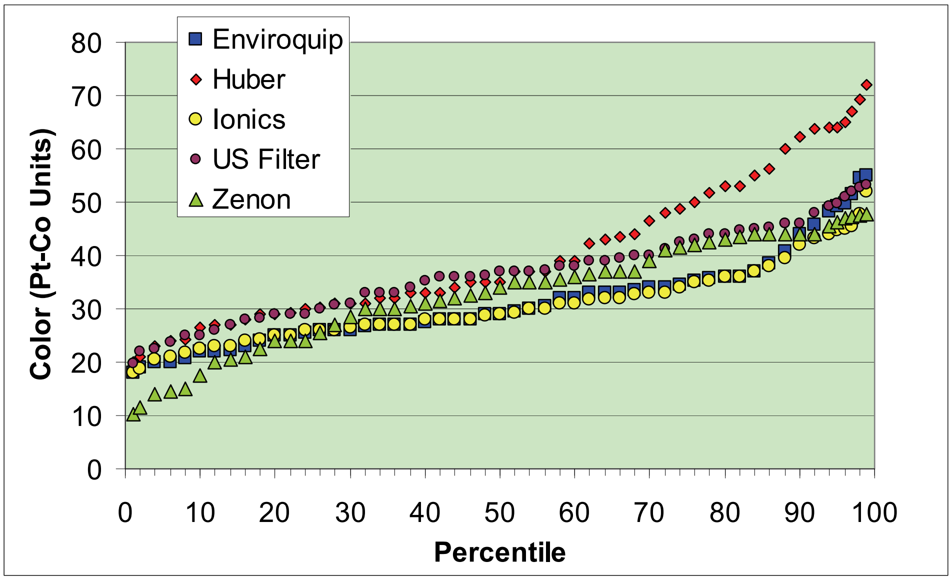

Figure 3.96. Effluent (permeate) color value distributions during Phase IC (primary effluent).

Turbidity. Effluent data for turbidity are shown in Figure 3.97. No reliable data were obtained for the US Filter or Zenon MBR pilot units during this phase. The data show the very low values of permeate turbidity that are typical for MBR systems. The figure indicates that all of the turbidity values are less than 0.2 NTU for each of the MBRs and that the performances of the three different types of MBRs are somewhat different. However, since all of the values are so low, it is difficult to infer anything from the differences. The turbidity value of 0.2 NTU (achieved 95% of the time) is significant since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, whereas membrane-filtered effluents require only 80 mW-s/cm^2. Based upon the data for Phase IA, these MBRs would qualify for the reduced UV disinfection dosage.

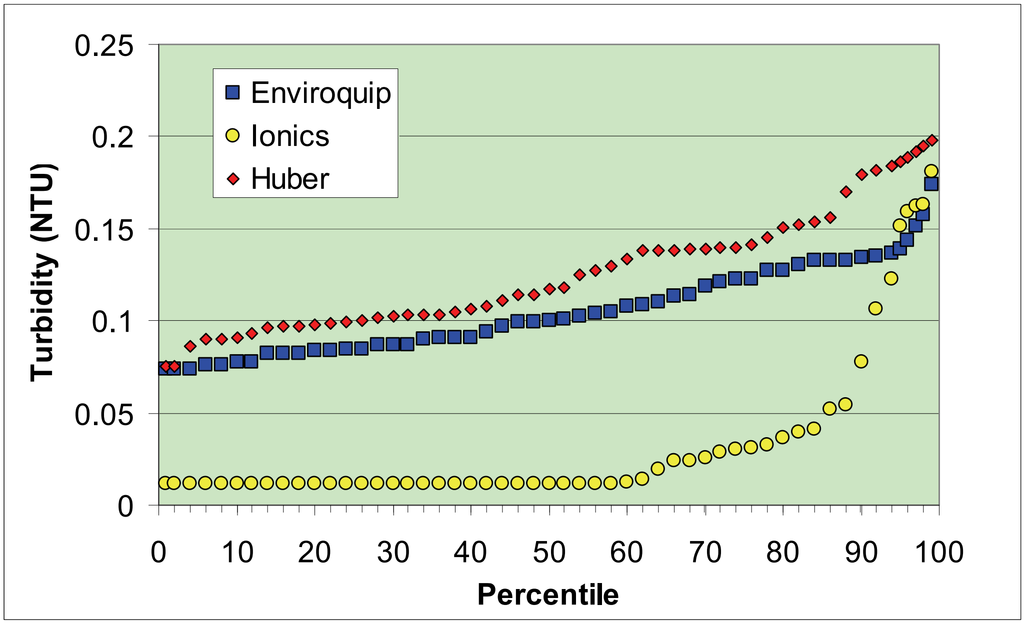

Figure 3.97. Effluent (permeate) turbidity distributions during Phase IC (primary effluent).

UVT. Influent and effluent UVT_{254} data are shown in Figures 3.98 and 3.99, respectively. The data indicate that the raw wastewater feed had a low UVT of between 25 and 45%, with an average of about 35%, indicating a large quantity of UV-absorbing material. Figure 3.98 shows the very high values of permeate UVT that are typical for MBR systems. The figure indicates that greater than 85 to 95% of the UVT values are greater than 65% for each of the MBRs and that the performances of the five different types of MBRs are very comparable. The UVT value of 65% is significant, since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, whereas membrane-filtered effluents require only 80 mW-s/cm^2. Based upon the data for Phase IA, these MBRs would qualify for the reduced UV disinfection dosage.

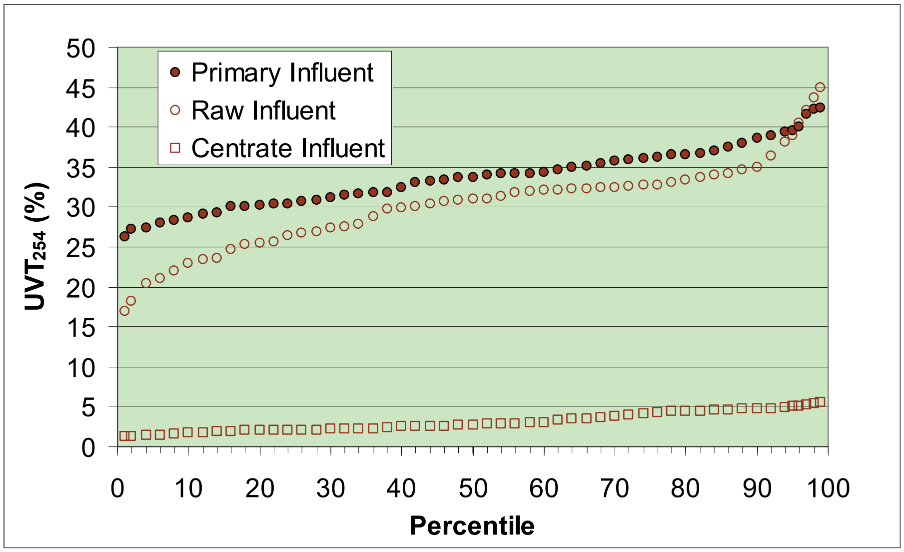

Figure 3.98. Primary effluent feed UVT_{254} distribution during Phase IC.

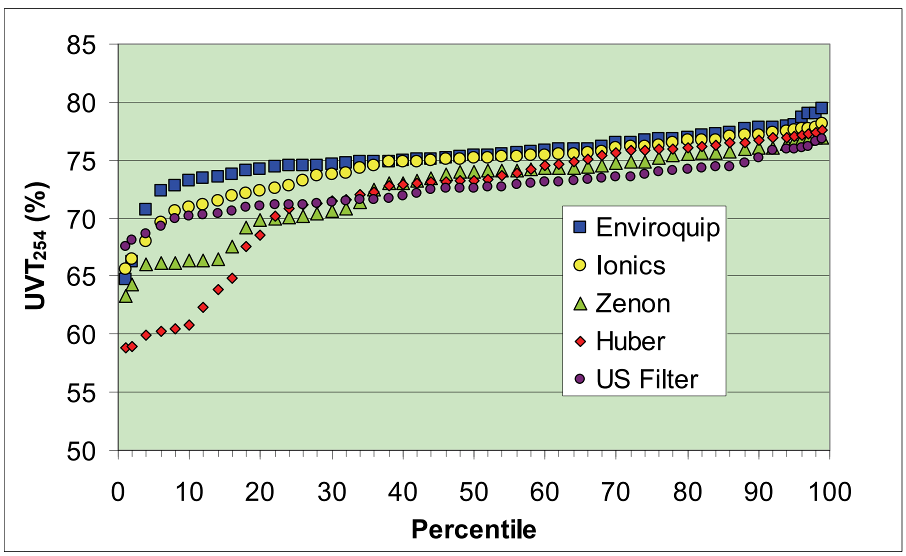

Figure 3.99. Effluent (permeate) UVT_{254} distributions during Phase IC (primary effluent).

O&G. Influent and effluent O&G data are shown in Figures 3.100 and 3.101, respectively. The data indicate that the primary effluent wastewater feed contained O&G concentrations between less than 10 mg/L and nearly 25 mg/L. These values are significantly lower than those for the raw wastewater feed. The effluent data indicate that O&G is completely removed by all of the MBRs nearly all of the time. The performances of the five different types of MBRs were very comparable.

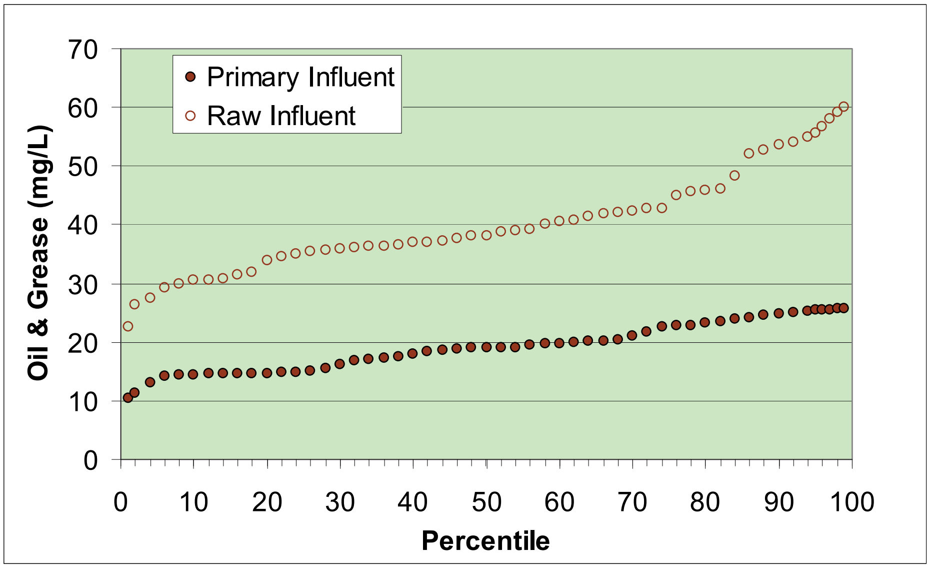

Figure 3.100. Primary effluent feed O&G distribution during Phase IC.

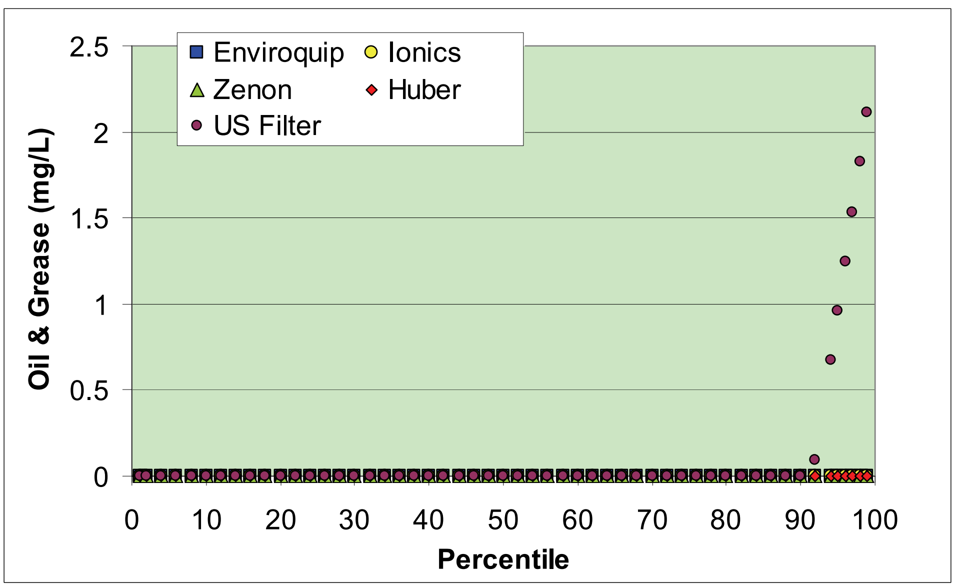

Figure 3.101. Effluent (permeate) O&G distributions during Phase IC (primary effluent).

Fecal coliform and coliphage. Fecal coliform and coliphage were not detected in the permeate from the MBRs, with the exception of only a few events for coliform that were subsequently attributed to sample contamination at the pilot site. Minimum, maximum, and average values for the influent are shown in Table 3.8. The values in Table 3.8 are somewhat lower than those for raw wastewater (Table 3.3).

Table 3.8. Influent and effluent fecal coliform and coliphage during Phase IC (primary effluent)

Type of Phase IC value	Value for: Fecal coliform (CFU/100 mL) in influent	Fecal coliform (CFU/100 mL) in effluent (all)	Fecal coliphage (PFU/100 mL) in influent	Fecal coliphage (PFU/100 mL) in effluent
Minimum value	1.1×10^6	<1	1.2×10^5	<1
Maximum value	7.7×10^7	3	6.4×10^5	<1
Avg. value	6.2×10^6	<1	3.6×10^5	<1

Alkalinity. Alkalinity was measured approximately monthly. Table 3.9 shows the alkalinity data collected during Phase IC. The data indicate that alkalinity was sufficient in the centrate feed and that there was alkalinity remaining in the MBR permeates

Table 3.9. Influent and effluent alkalinity data for Phase IC (primary effluent)

Date (mo-day-yr)	Concn (in mg/L) of $CaCO_3$ in: Influent	Enviroquip effluent	Huber effluent	Ionics effluent	US Filter effluent	Zenon effluent
9-30-04	184	33	NA	43	163	35
10-15-04	175	51	32	25	92	66
11-15-04	168	39	142	44	181	NA
12-15-04	175	44	92	83	NA	NA
1-19-05	197	89	44	57	NA	NA
Avg.	180	51	78	50	145	51

Overall average water quality and removal efficiencies. Table 3.10 gives the overall average values of influent and effluent for all the water quality parameters discussed above. Table 3.10 also shows the average removal efficiencies for the same parameters where appropriate.

Table 3.10. Average water quality data and removal efficiencies during Phase IC (primary effluent)

Analyte	Value for:					
	Influent	Enviroquip	Huber	Ionics	US Filter	Zenon
BOD_5 (mg/L)	127	0.98 (99.2%)	1.7 (98.7%)	1.2 (99.1%)	2.7 (97.9%)	1.9 (98.5%)
TSS (mg/L)	57	0.80 (98.6%)	1.0 (98.2%)	1.0 (98.2%)	2.0 (96.5%)	1.4 (97.5%)
TOC (mg/L)	33.4	4.1 (88%)	6.6 (80%)	3.6 (89%)	6.3 (81%)	5.7 (83%)
O&G (mg/L)	18.9	0 (100%)	0 (100%)	0 (100%)	0.18 (99%)	0 (100%)
Nitrogen, total (mg of N/L)	28.2	17.8 (37%)	17.6 (38%)	21.5 (24%)	14.3 (49%)	17.3 (39%)
Ammonia (mg of N/L)	21.8	0.04	7.0	0.79	7.9	2.4
Nitrate (mg of N/L)	NA	15.5	2.8	8.4	4.7	17.0
Phosphorus, total (mg of P/L)	3.7	3.1 (16%)	2.5 (32%)	2.9 (22%)	2.0 (46%)	2.6 (30%)
Orthophosphorus (mg of P/L)	NA	2.7	2.5	2.9	1.2	2.6
Color (Pt-Co)	NA	31	40	31	36	32
UVT_{254} (%)	33.6	75.2	71.8	74.4	72.5	72.3
Turbidity (NTU)	NA	0.11	0.13	0.03	NA	NA
Fecal coliform (CFU/100 mL)	6.2×10^6	<1	<1	<1	<1	<1
Coliphage (PFU/100 mL)	3.6×10^5	<1	<1	<1	<1	<1
Alkalinity (mg of $CaCO_3$/L)	180	51	78	50	145	51

3.3 WATER QUALITY DATA REEVALUATION

The Project Advisory Committee (PAC) observed that during Phase I steady-state conditions were generally not achieved. The PAC also noted that it would be desirable to correlate the results with SRT or solid concentration or other parameters to determine if permeate water quality variability was reduced under “optimal” conditions. The goal of the reevaluation was to determine whether additional information can be obtained from the existing data.

We first looked into the permeate organic data. Figures 3.102 to 3.106 show permeate BOD concentrations as a function of MLSS for the various MBRs. Here, MLSS is used as a surrogate for SRT (which was not routinely determined) as the main controllable biological operating condition. Figure 3.106 shows that there may have been some differences in performance as a function of MLSS for the Enviroquip MBR. Figure 3.106 shows the permeate distributions for different ranges of MLSS values and indicates that the lower solid ranges generally provided better performance than did both the higher solid ranges and the overall distribution for all MLSS values. The permeate BOD values were larger when the MLSS was greater than 10 g/L during treatment of raw wastewater. However, this was apparently not the case when the facility was treating primary effluent, in which case the BOD values were all consistently low. In the case of centrate wastewater feed, there appeared to be greater variability in permeate BOD over the whole range of MLSS values employed. Figures 3.102 through 3.105 do not reveal any ranges of MLSS that are “optimum” for BOD removal for Ionics, Zenon, Huber, or US Filter. Figure 3.108 shows poor correlation between raw influent BOD and permeate BOD. Instead, the variability in permeate BOD could be indicative of variability in influent “refractory” BOD that was not quantified here. Figures 3.109 to 3.113 show a lack of general correlation between permeate TOC and MLSS. Figure 3.114 indicates a lack of correlation between permeate COD and MLSS. Similarly, the effluent UVT does not seem to be correlated to MLSS (see Figures 3.115 to 3.117). We also looked at permeate solid concentrations that did not appear to be correlated with MLSS (see Figures 3.118 to 3.122). The conclusion after revisiting the data to determine optimal operating conditions was that no such conditions were distinguishable in our data sets.

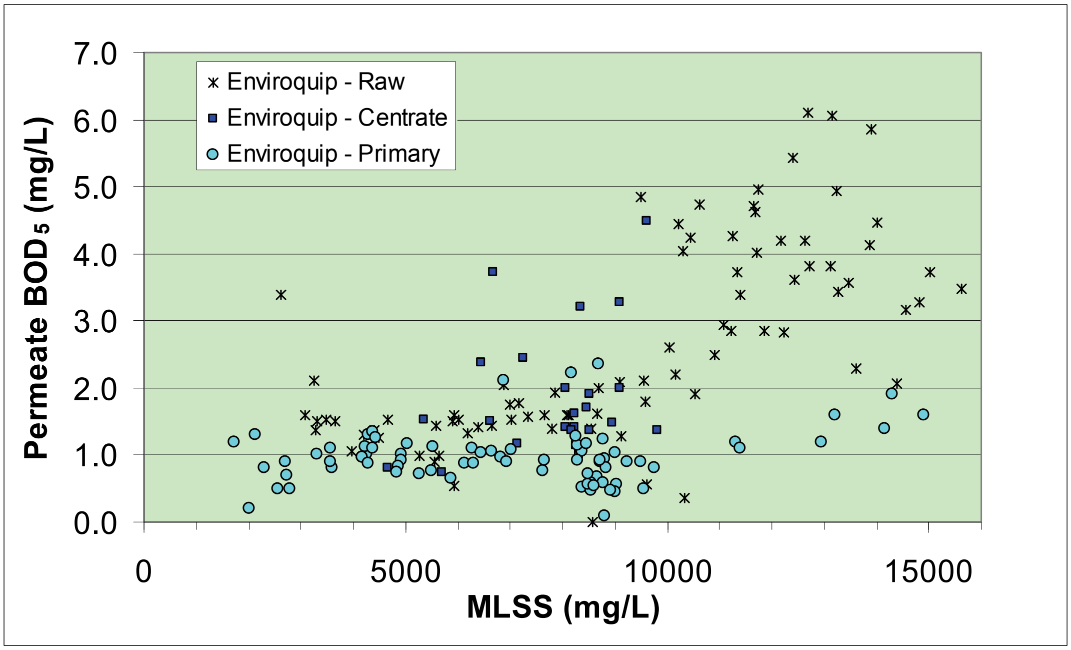

Figure 3.102. Permeate BOD concentrations as a function of MLSS for Enviroquip MBR.

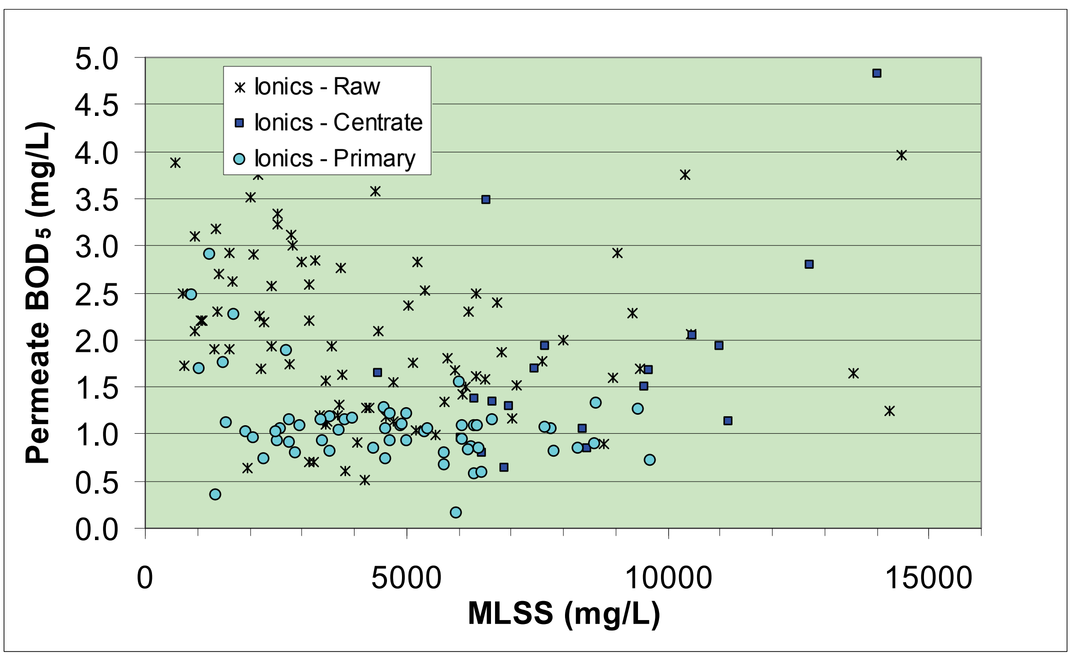

Figure 3.103. Permeate BOD concentrations as a function of MLSS for Ionics MBR.

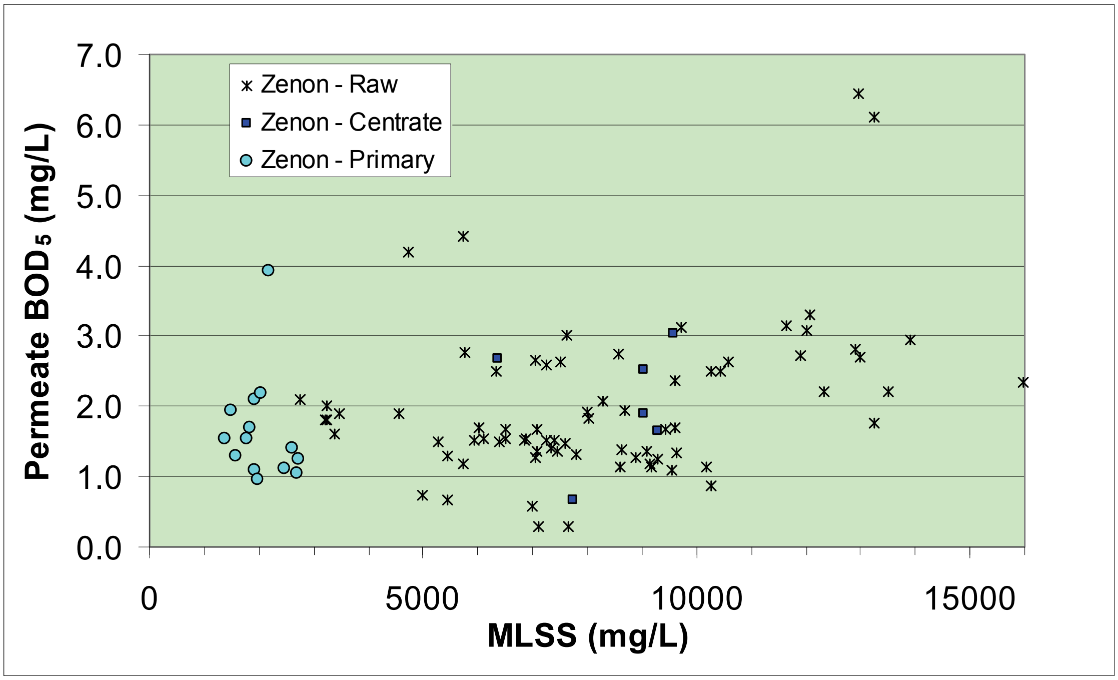

Figure 3.104. Permeate BOD concentrations as a function of MLSS for Zenon MBR.

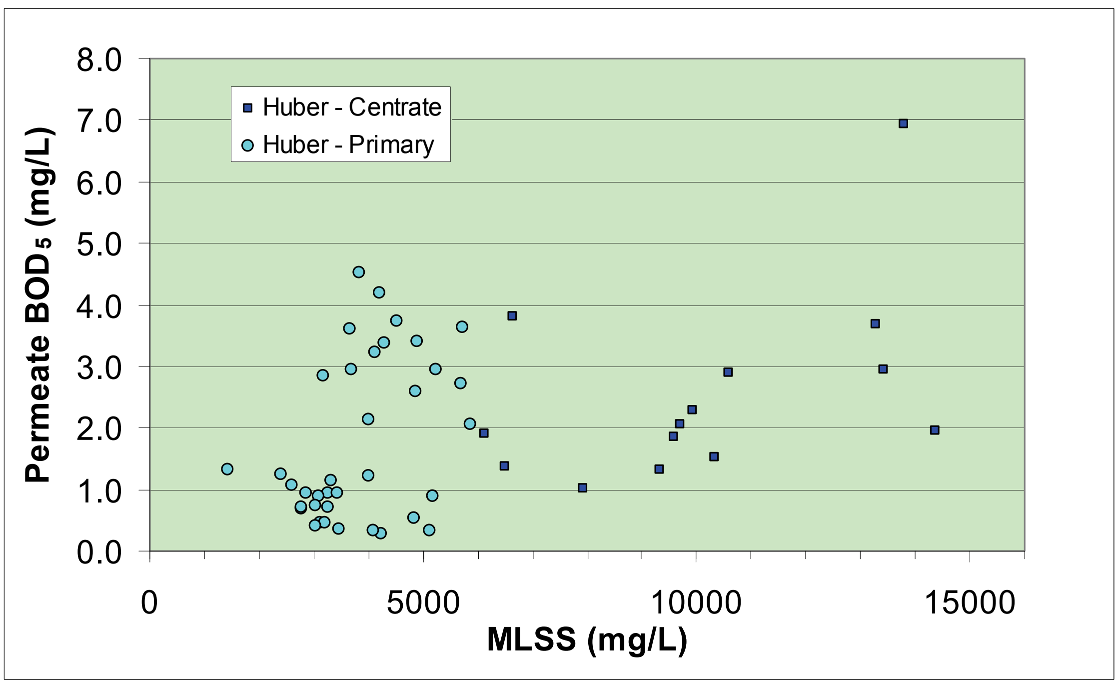

Figure 3.105. Permeate BOD concentrations as a function of MLSS for Huber MBR.

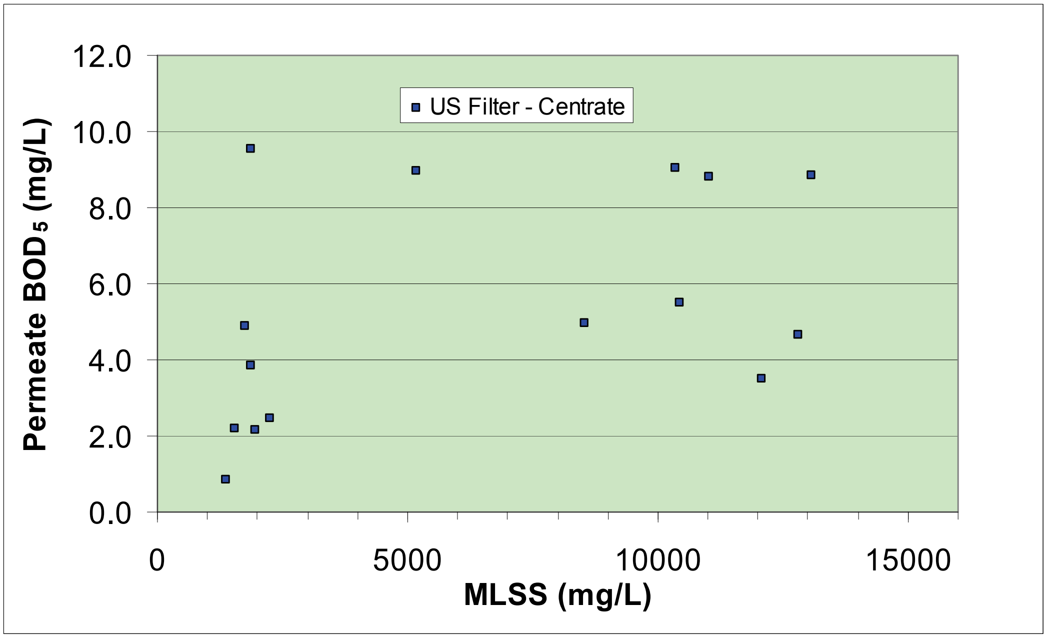

Figure 3.106. Permeate BOD concentrations as a function of MLSS for US Filter MBR.

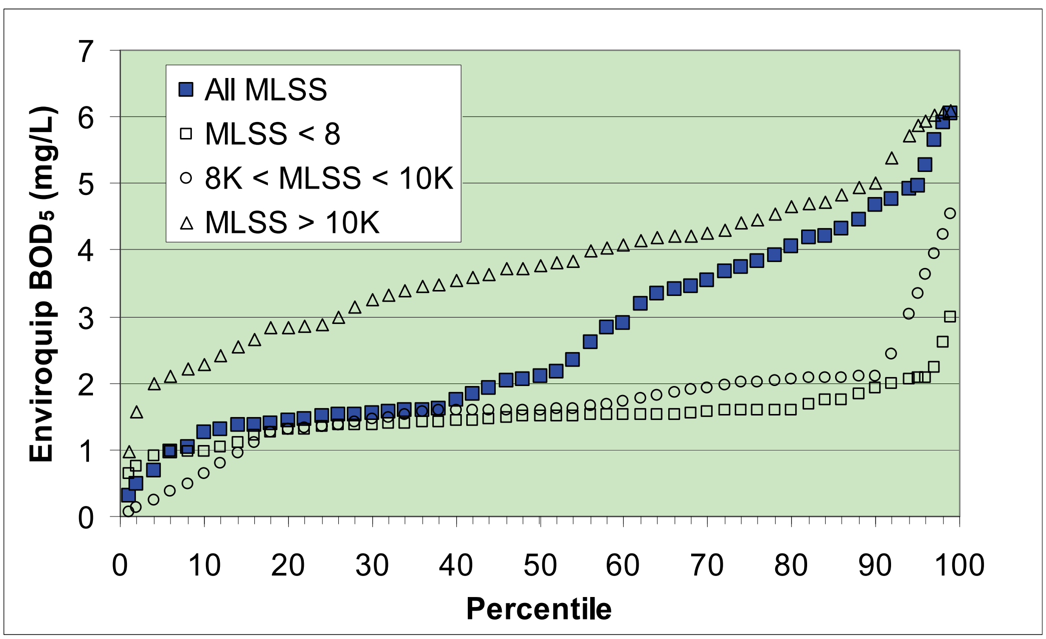

Figure 3.107. Permeate BOD for different MLSS ranges as a function of MLSS for Enviroquip MBR.

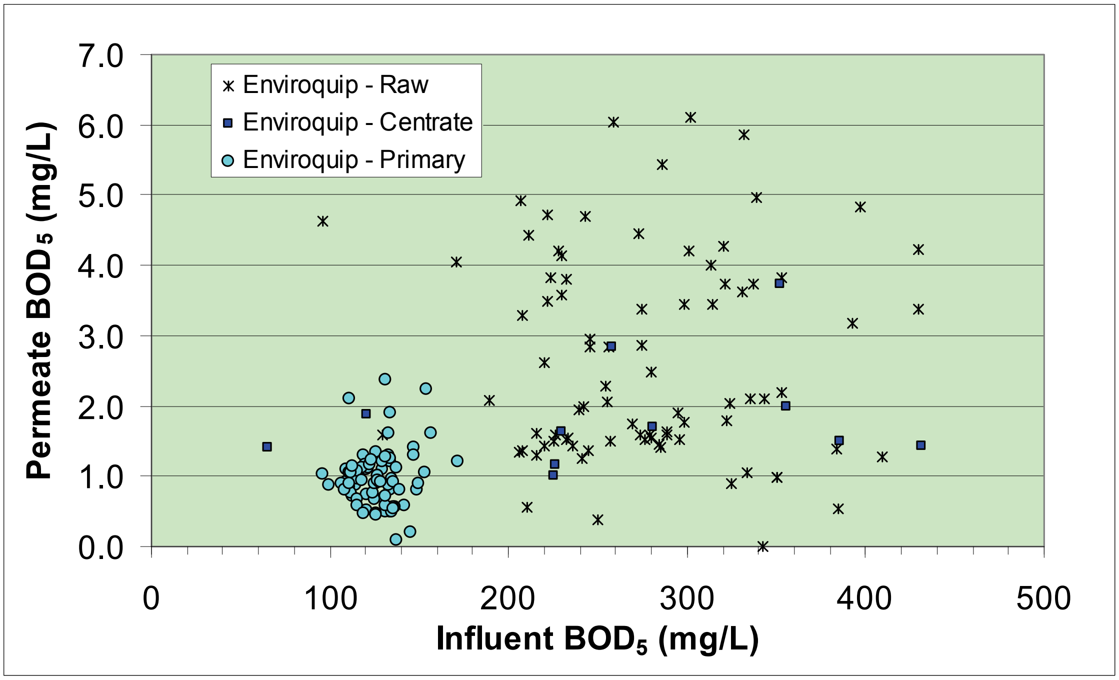

Figure 3.108. Permeate BOD as a function of influent BOD for Enviroquip MBR treating raw wastewater.

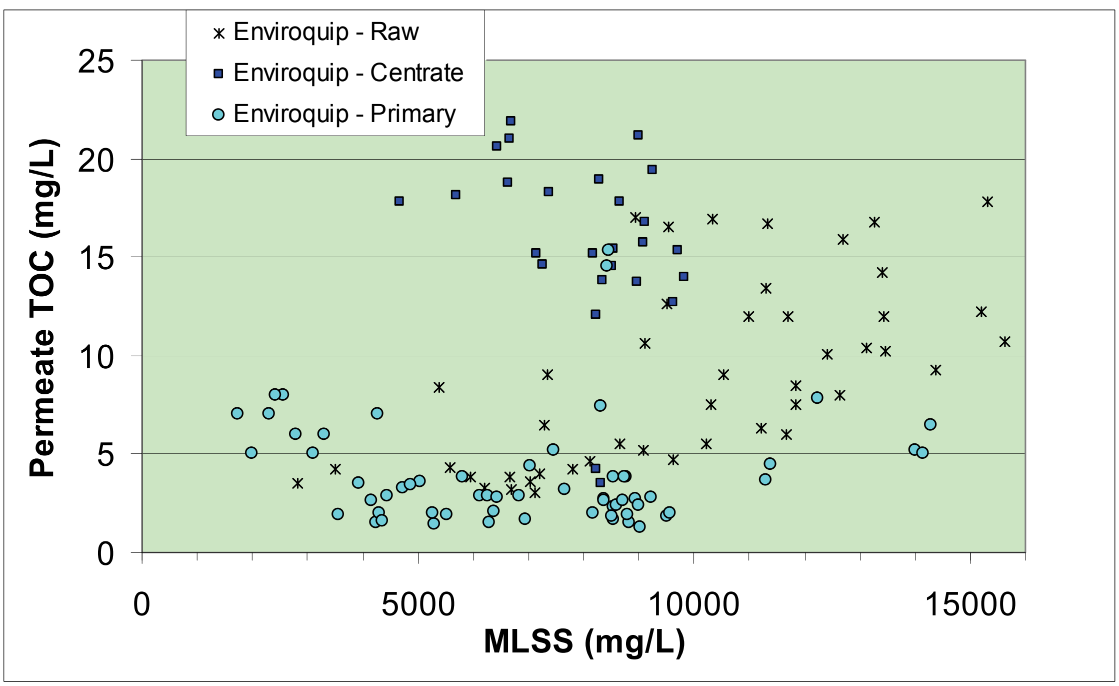

Figure 3.109. Permeate TOC concentrations as a function of MLSS for Enviroquip MBR.

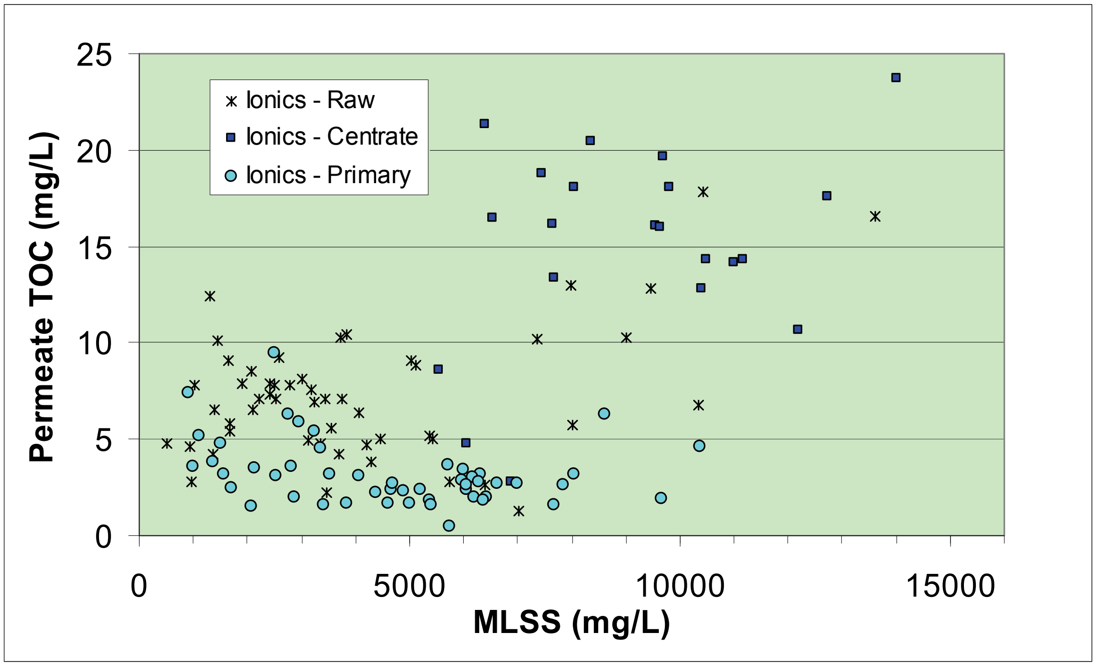

Figure 3.110. Permeate TOC concentrations as a function of MLSS for Ionics MBR.

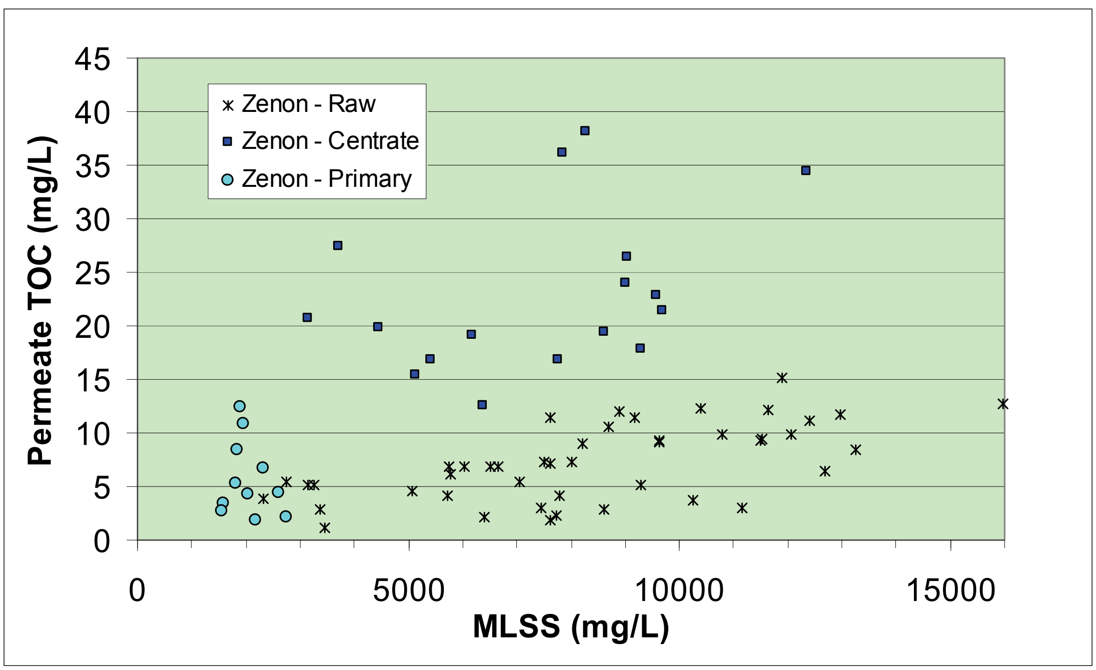

Figure 3.111. Permeate TOC concentrations as a function of MLSS for Zenon MBR.

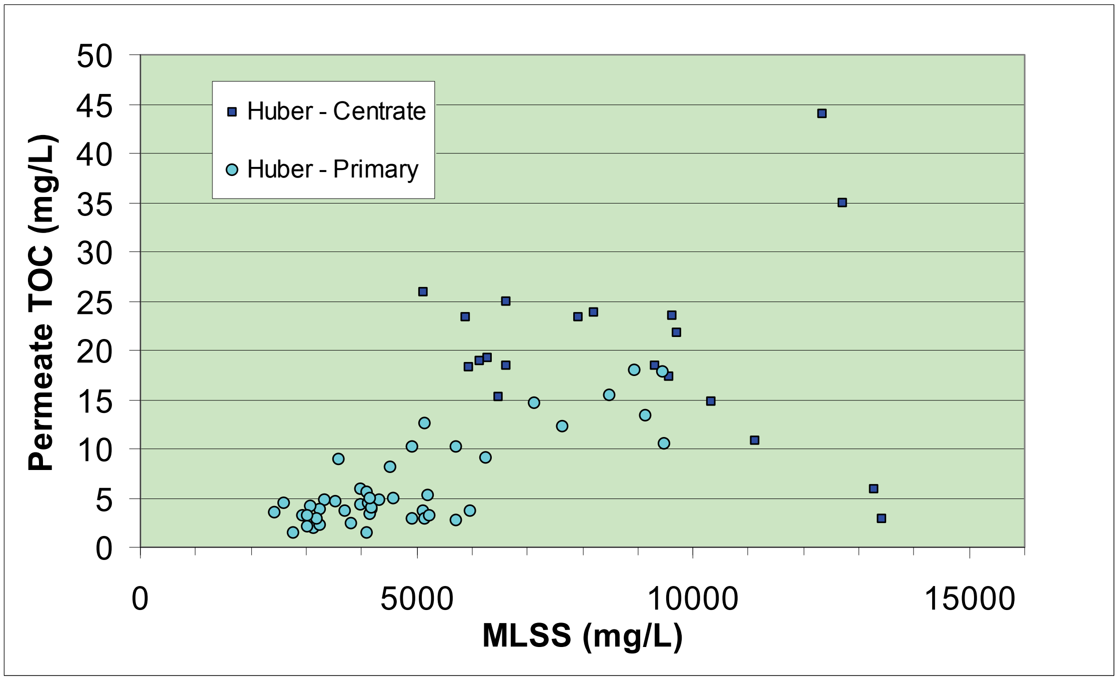

Figure 3.112. Permeate TOC concentrations as a function of MLSS for Huber MBR.

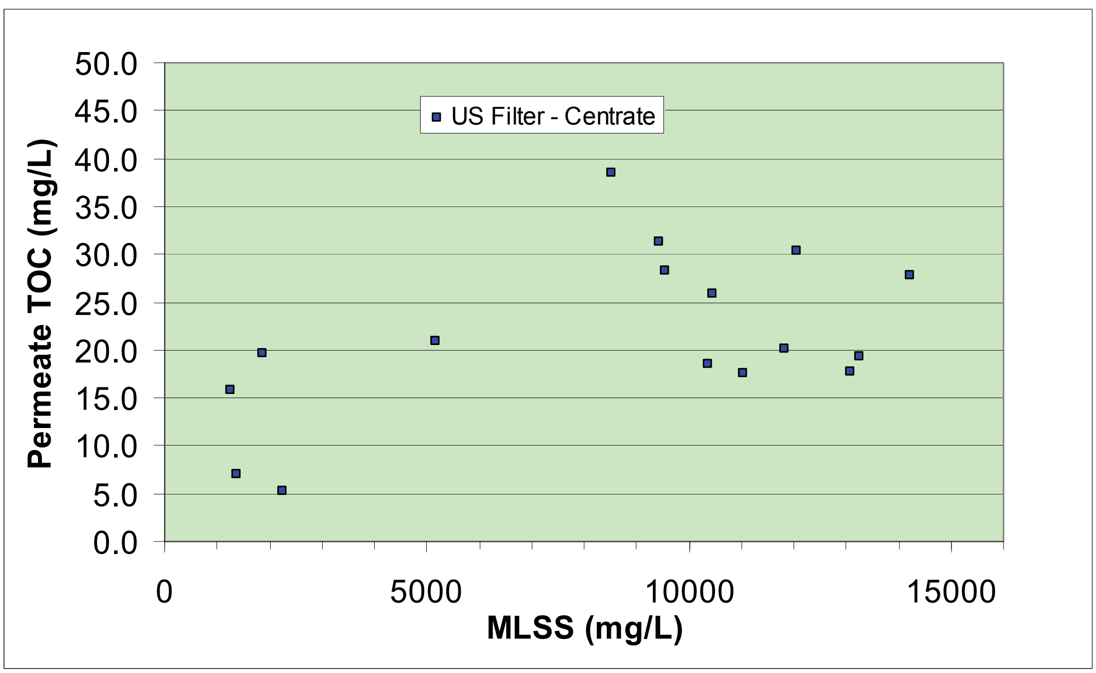

Figure 3.113. Permeate TOC concentrations as a function of MLSS for US Filter MBR.

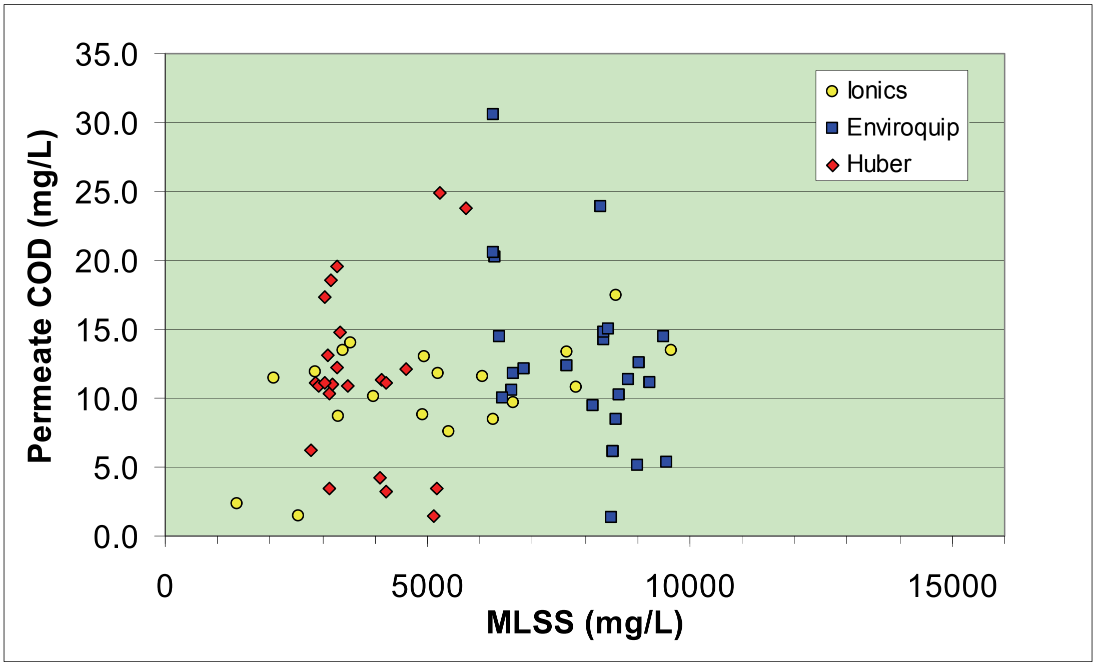

Figure 3.114. Permeate COD concentrations as a function of MLSS for Enviroquip, Ionics, and Huber MBRs treating primary effluent wastewater.

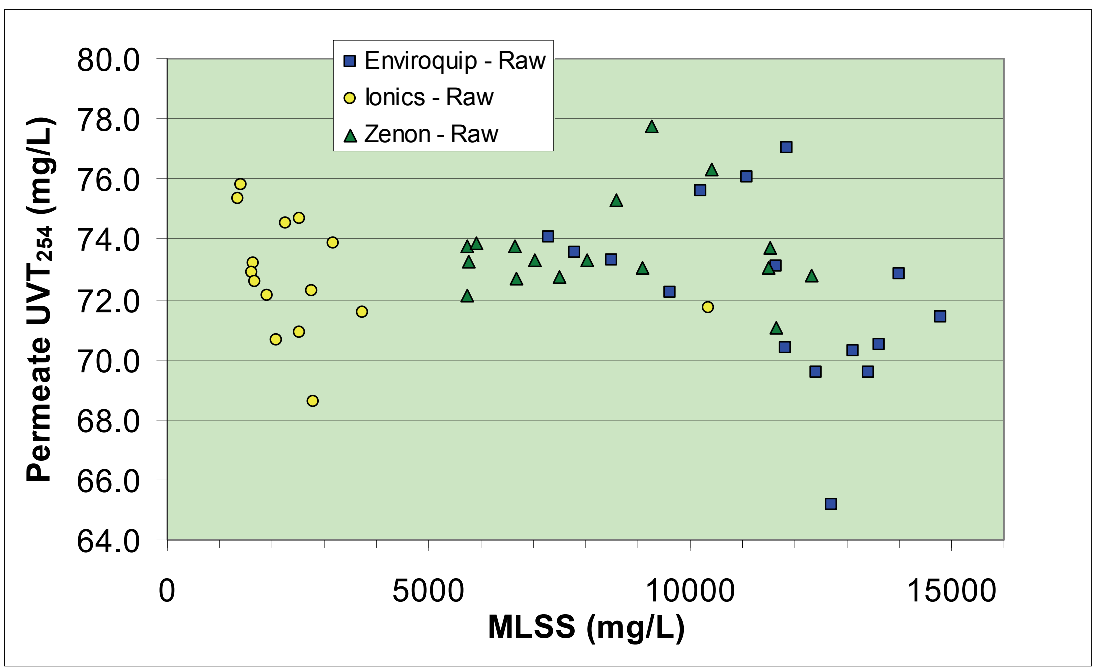

Figure 3.115. Permeate UVT_{254} as a function of MLSS for Enviroquip, Ionics, and Zenon MBRs treating raw wastewater.

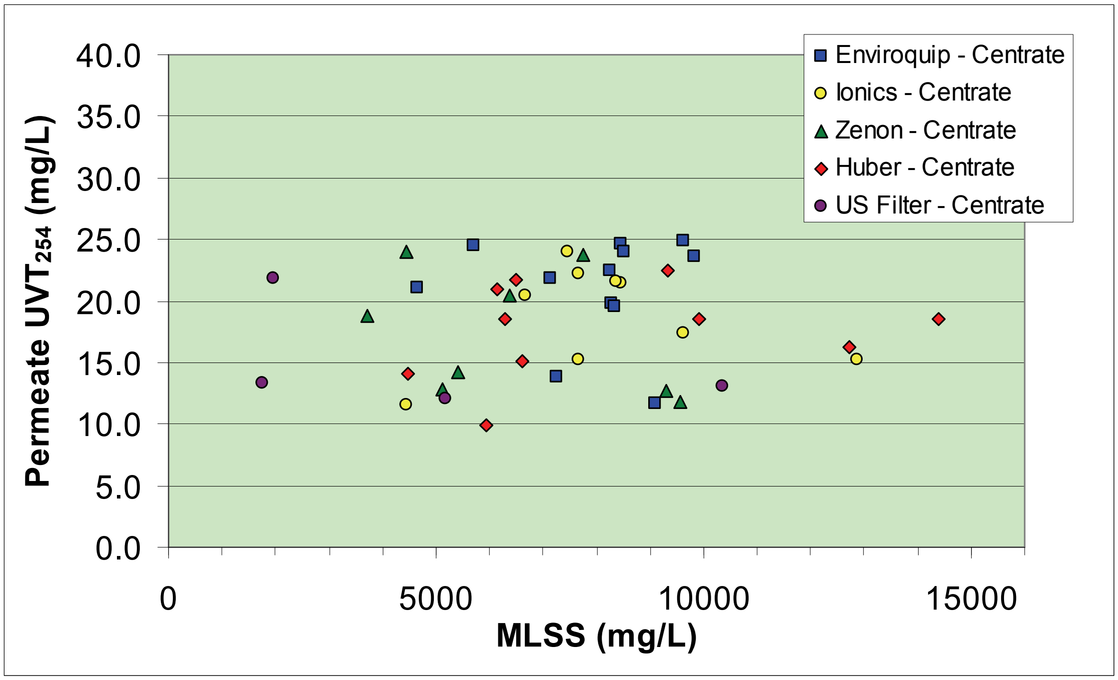

Figure 3.116. Permeate UVT_{254} as a function of MLSS for Enviroquip, Ionics, Zenon, and Huber MBRs treating centrate wastewater.

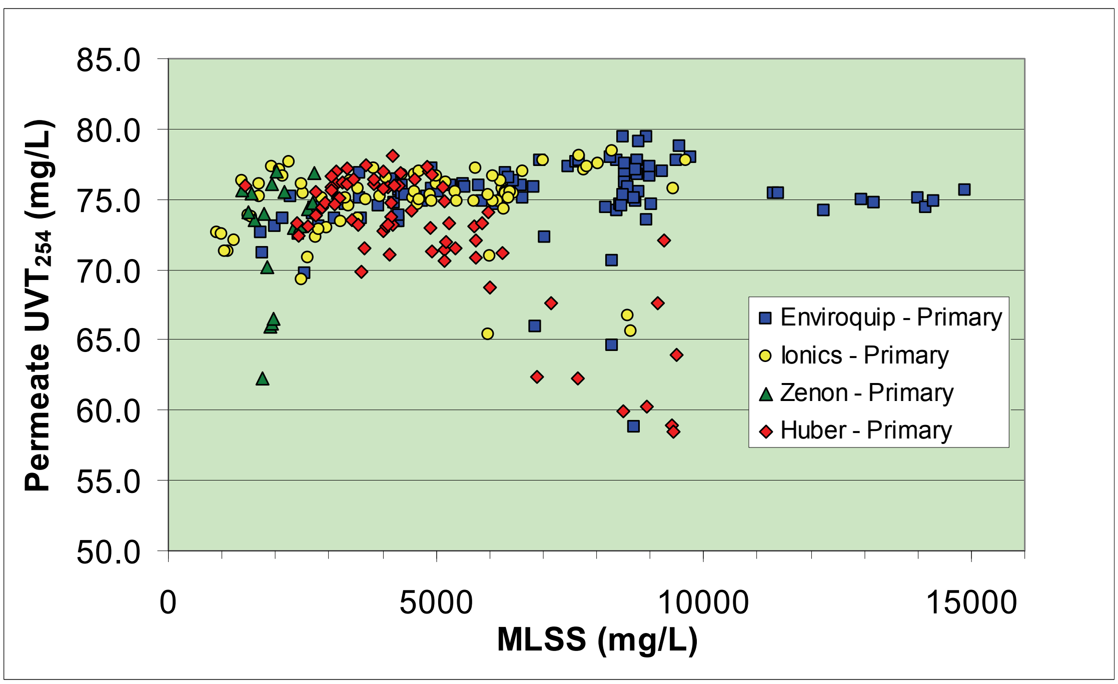

Figure 3.117. Permeate UVT_{254} as a function of MLSS for Enviroquip, Ionics, Zenon, and Huber MBRs treating primary wastewater.

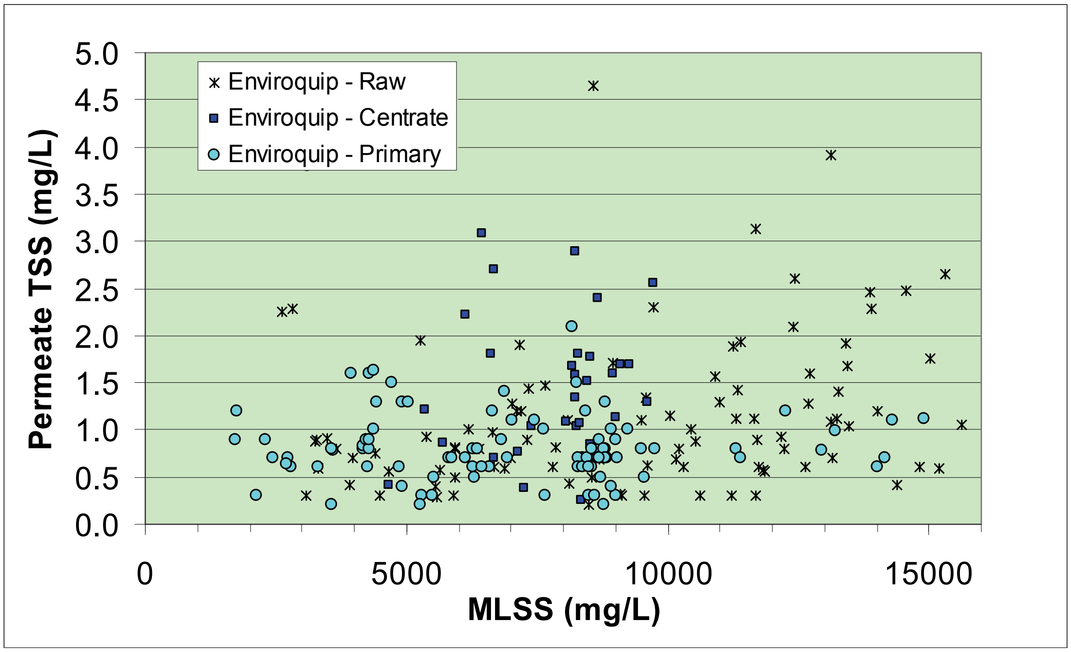

Figure 3.118. Permeate TSS concentrations as a function of MLSS for Enviroquip MBR.

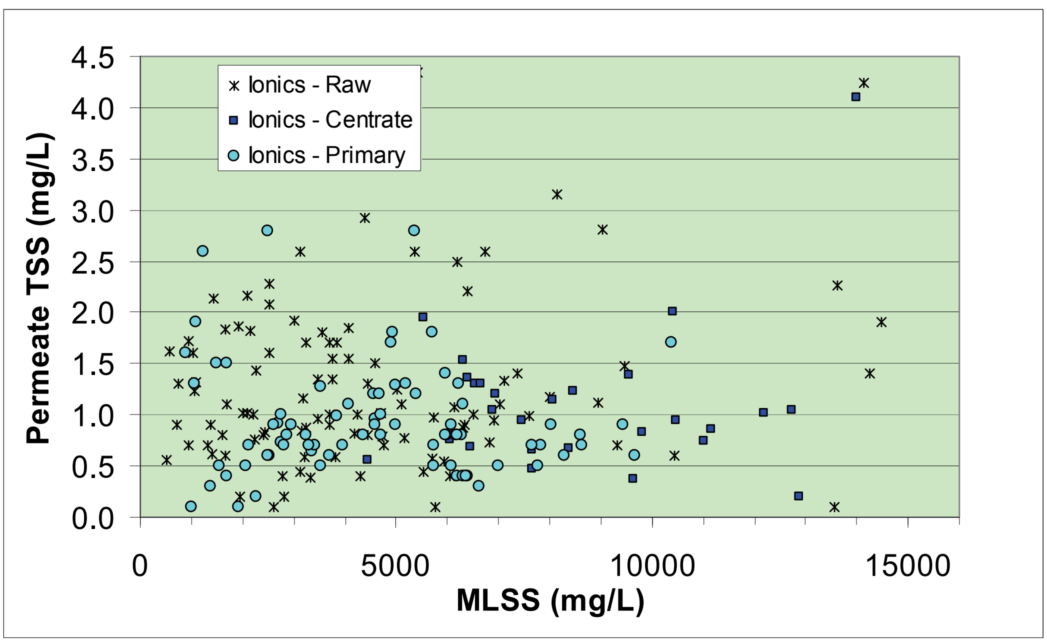

Figure 3.119. Permeate TSS concentrations as a function of MLSS for Ionics MBR.

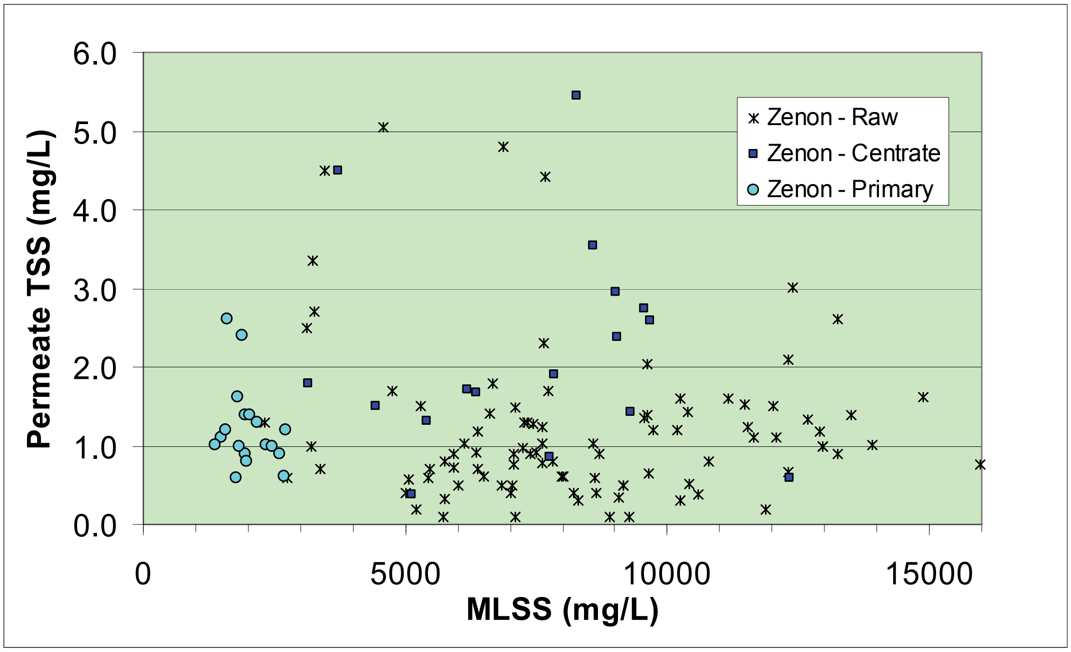

Figure 3.120. Permeate TSS concentrations as a function of MLSS for Zenon MBR.

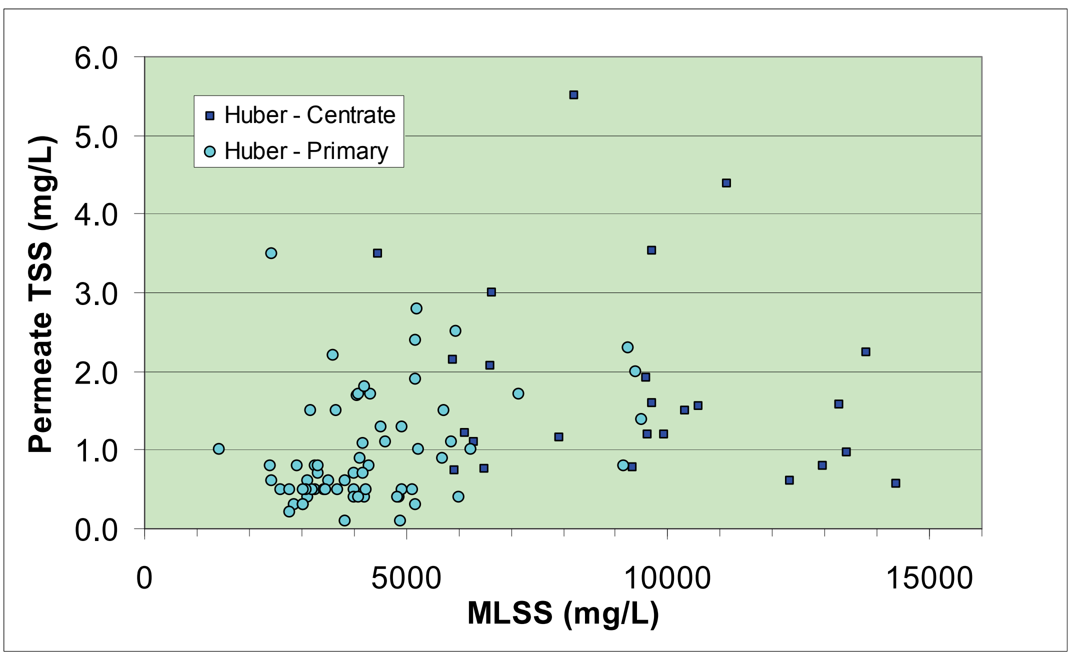

Figure 3.121. Permeate TSS concentrations as a function of MLSS for Huber MBR.

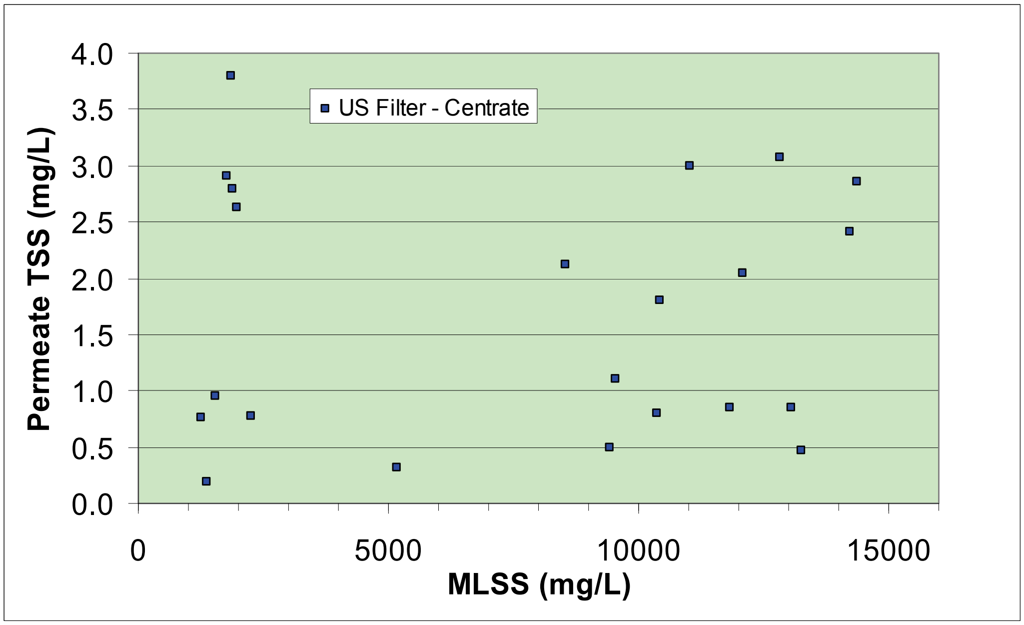

Figure 3.122. Permeate TSS concentrations as a function of MLSS for US Filter MBR.

CHAPTER 4

RESULTS AND DISCUSSION: PHASE II

4.1 EVALUATION OF ZENON MBR AT TWO OTHER LOCATIONS

One of the proposed goals of the Honolulu MBR Pilot Study was to pilot test individual or possibly pairs of MBRs at actual full-scale application sites as needed to develop site-specific design criteria as part of procurement processes. While there were several agencies and owners who expressed interest in this during the study, few actual opportunities came to fruition. The Zenon pilot MBR was moved to the SBWWTP for procurement-based testing. A second Zenon pilot MBR was later shipped to Hawaii for evaluation at a pump station in Wahiawa that serves the SBWWTP as part of the same full-scale design. Notably, the 4.0-MGD SBWWTP has now been retrofitted as an MBR plant and went into service in January 2007. This chapter describes the data collected during these evaluations.

4.1.1 SBWWTP

The goal of this portion of the study was to give the operations staff at the SBWWTP the opportunity to become familiar with the Zenon equipment in conjunction with design and procurement of a full-scale (4-MGD) retrofit of the plant with Zenon MBR equipment. This portion of the Phase II study was conducted from December 1, 2004, to February 22, 2005. The pilot MBR was operated continuously during this period. The full-scale MBR system is designed to treat primary effluent; therefore, the pilot was operated likewise. A 1.0-mm-pore-size fine screen was used for pretreatment of primary effluent wastewater (flow equalization with aeration, 2-in. coarse screen, grit removal, and primary clarification) in this phase. The main water quality goals were to reduce BOD and TSS to less than 5 mg/L and turbidity to less than 0.2 NTU, keep UVT at greater than 65%, and have <1 fecal coliform CFU/100 mL. There were no nutrient removal goals, and no attempt was made to optimize pilot MBR operations for nutrient removal.

The data are divided into process operating data and water quality data. The process operating data include flux, TMP, MLSSs, and DO concentrations. The water quality data include influent and effluent BOD_5, COD, TSS, total-N, ammonia-N, nitrate-N, total-P, orthophosphorus, turbidity, UVT_{254}, alkalinity, pH, fecal coliform, and total coliform.

4.1.1.1 Process Operating Data

The Zenon MBR was operated at its design flux of 10 GFD. MBRs are generally operated by maintaining a target MLSS rather than a target SRT. The Zenon pilot unit was operated at an MLSS between 5000 and 13,000 mg/L in this portion of the study (see Figure 4.1). The DO data are shown in Figure 4.2.

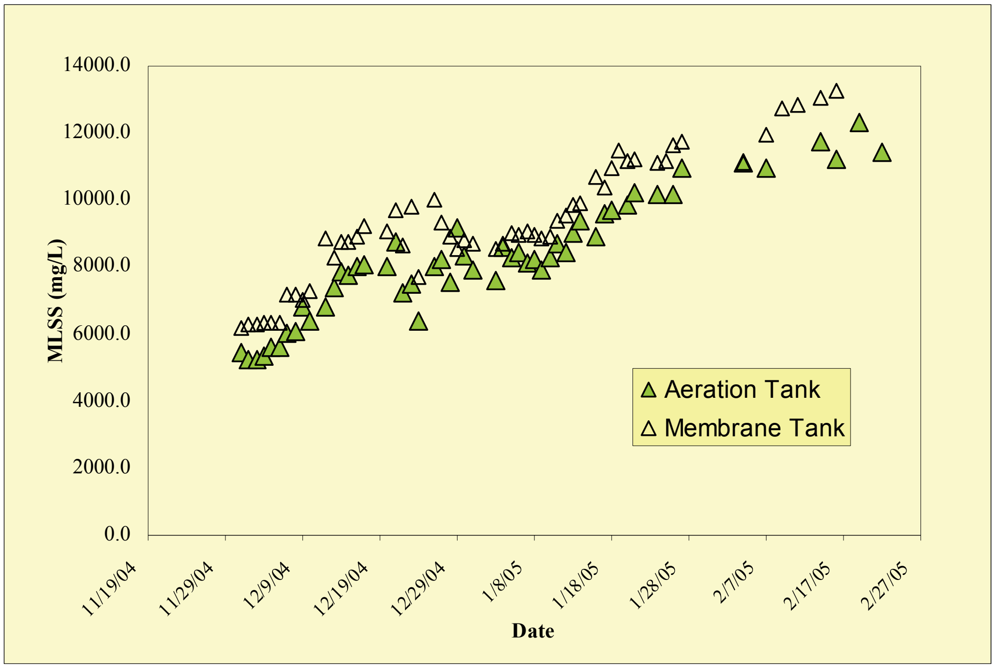

Figure 4.1. Mixed liquor TSS concentrations during Phase II (SBWWTP primary effluent).

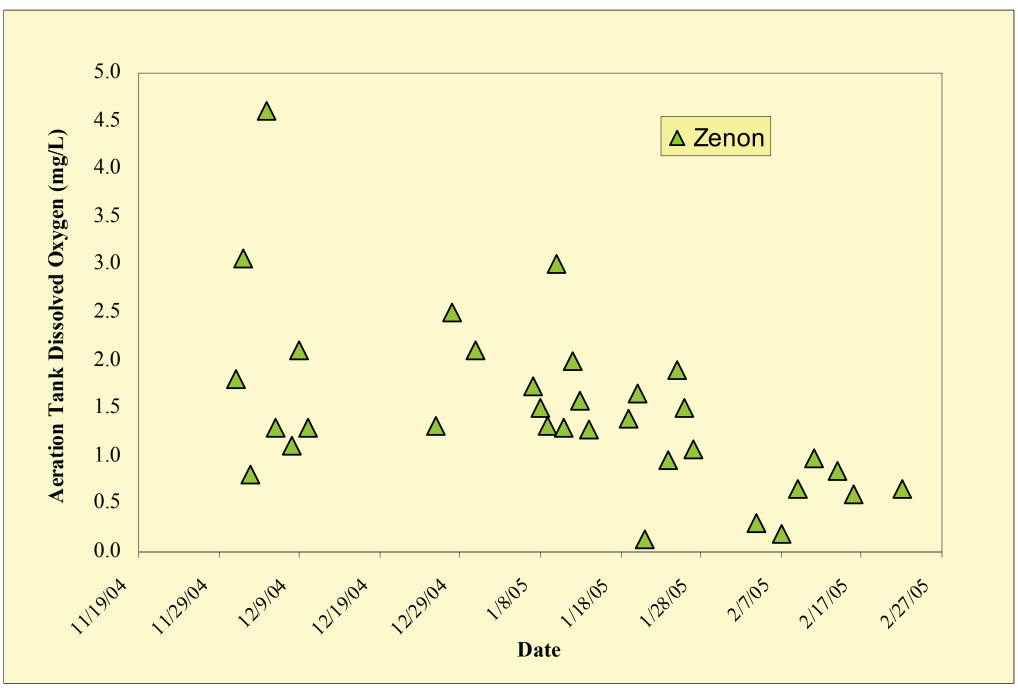

Figure 4.2. Mixed liquor DO during Phase II (SBWWTP primary effluent).

4.1.1.2 Water Quality Data

The water quality data are presented in Figures 4.3 through 4.21 and Tables 4.1 and 4.2. Overall, the effluent (permeate) water quality produced by the Zenon MBR was excellent by industry standards for secondary effluent and/or filtered secondary (tertiary) effluent. The data are presented graphically in chronological order. Overall average influent and effluent values and overall removal efficiencies for all of the water quality parameters analyzed are reported in Table 4.2 at the end of the section.

BOD. Influent and effluent BOD_5 data are shown in Figures 4.3 and 4.4, respectively. The data indicate that the primary effluent feed was of low strength and that the BOD_5 averaged just 69 mg/L. Figure 4.4 shows the very low values of effluent BOD_5 that are typical for MBR systems. The figure indicates that most of the BOD_5 values are less than 3 mg/L, with an average of just 2.0 mg/L.

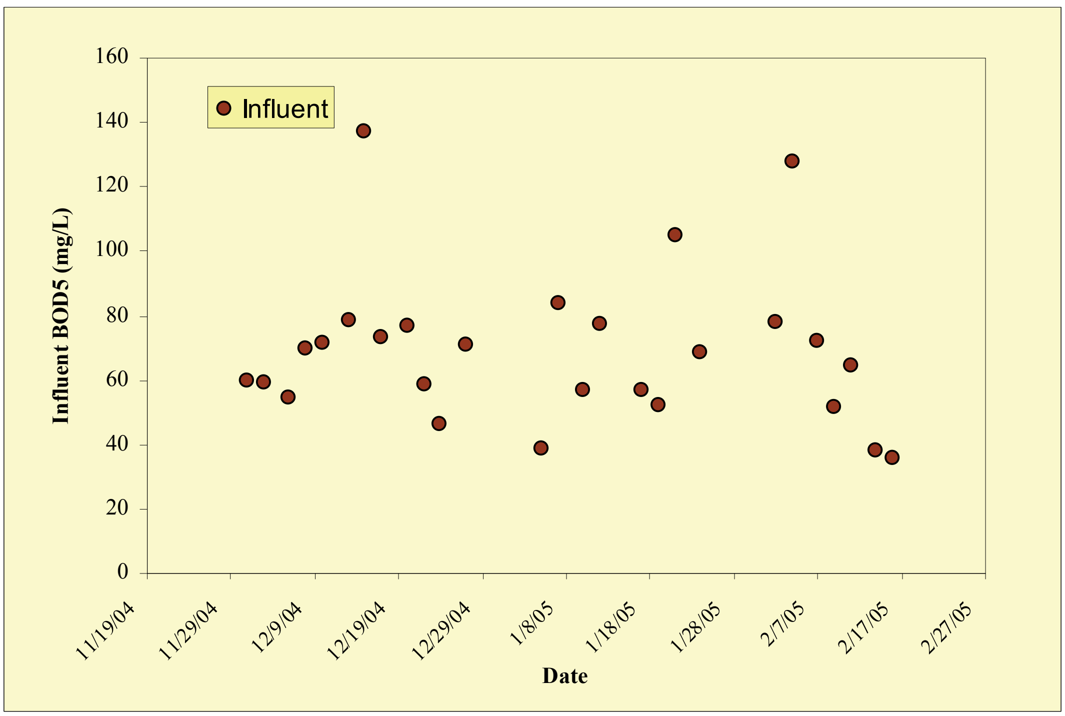

Figure 4.3. Influent BOD_5 concentrations during Phase II (SBWWTP primary effluent).

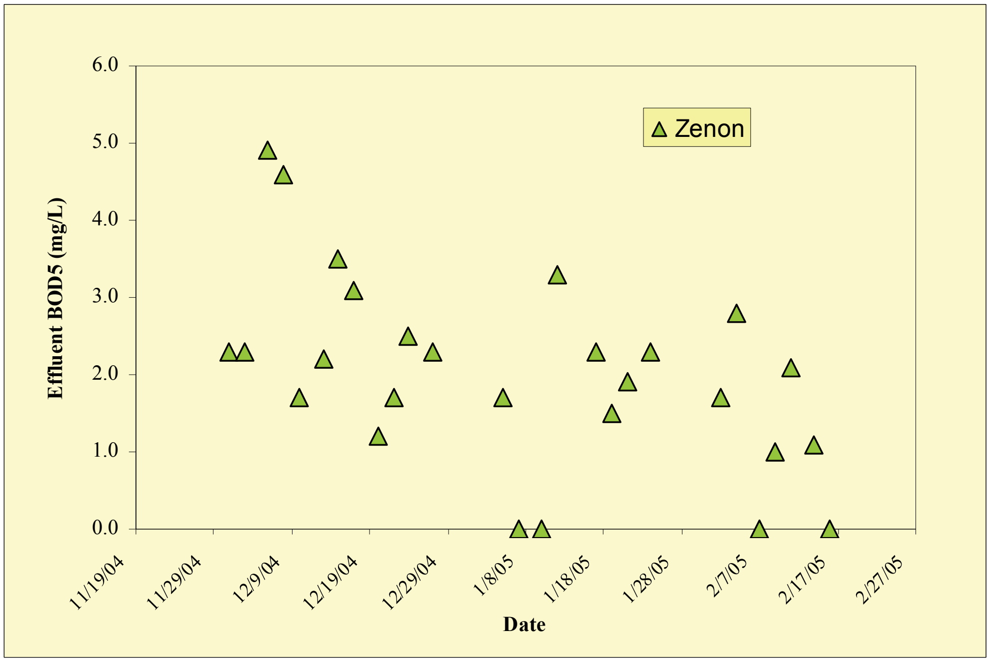

Figure 4.4. Effluent (permeate) BOD_5 concentrations during Phase II (SBWWTP primary effluent).

COD. Influent and effluent COD data are shown in Figures 4.5 and 4.6, respectively. The data indicate that the COD varied between approximately 100 and 250 mg/L. Figure 4.6 shows that the MBR permeates contain small yet significant amounts of oxygen-demanding materials. This finding could mean that a small amount of soluble organic matter that is not readily degradable as BOD_5 passes through the MBR system. This amount is often denoted as SMP that can be fractionated into carbohydrates, proteins, and lipids.

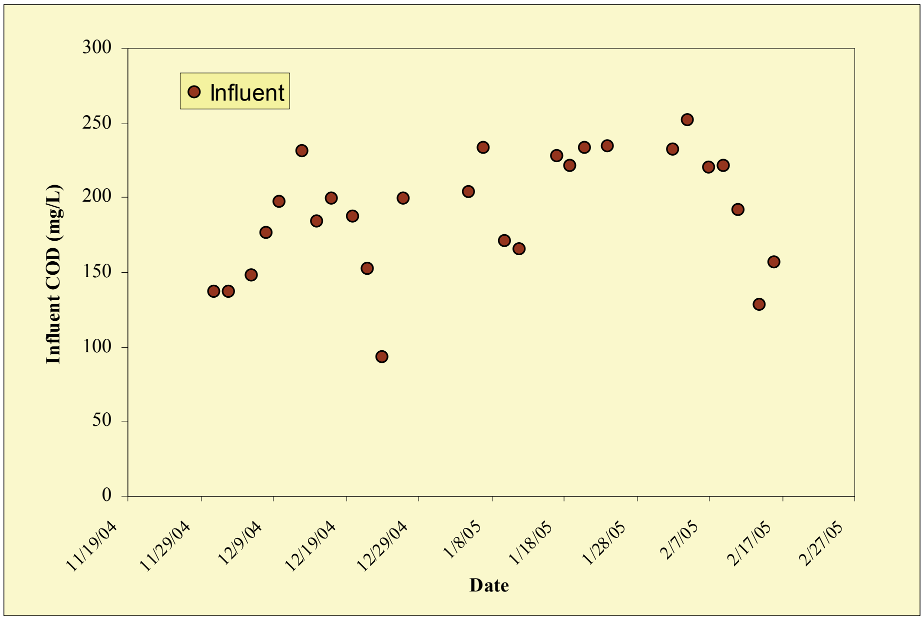

Figure 4.5. Influent COD concentrations during Phase II (SBWWTP primary effluent).

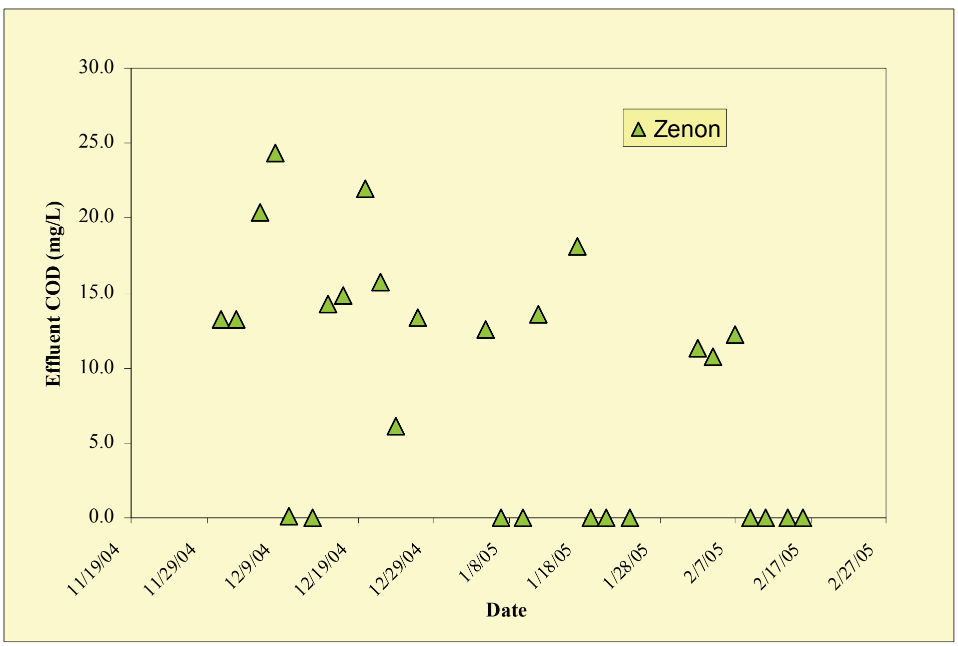

Figure 4.6. Effluent (permeate) COD concentrations during Phase II (SBWWTP primary effluent).

TSS. Influent and effluent TSS data are shown in Figures 4.7 and 4.8, respectively. The data indicate that the primary effluent feed was of low strength and that the TSS varied between approximately 20 and 100 mg/L. Figure 4.8 shows the very low values of effluent TSS that are typical for MBR systems. The figure indicates that all but one of the effluent TSS values are below the detection limit of 1 mg/L.

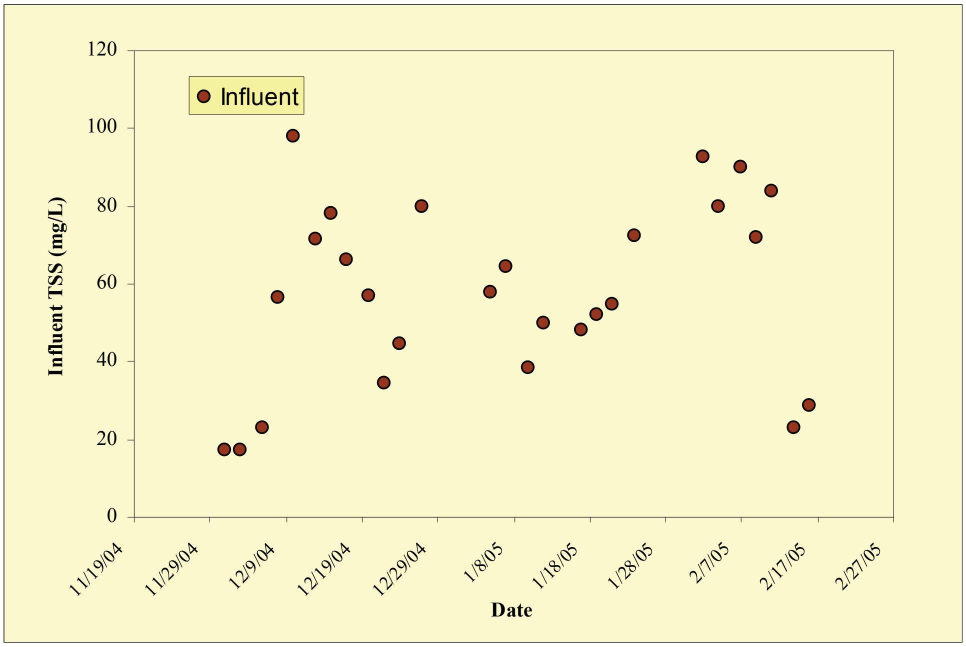

Figure 4.7. Influent TSS concentrations during Phase II (SBWWTP primary effluent).

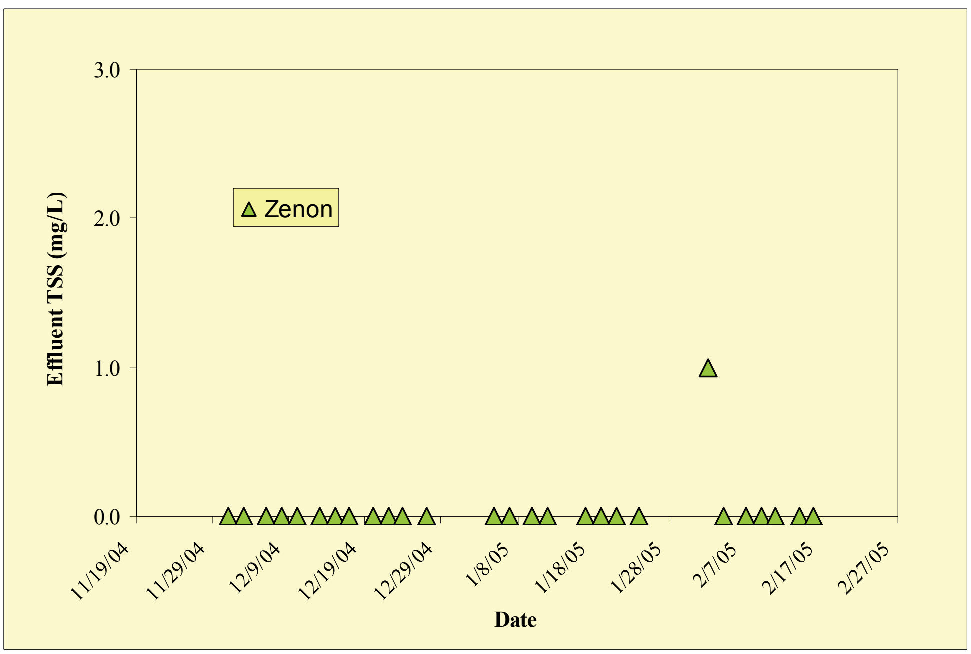

Figure 4.8. Effluent (permeate) TSS concentrations during Phase II (SBWWTP primary effluent).

Nitrogen species. Influent and effluent data for total nitrogen are shown in Figures 4.9 and 4.10, respectively. Influent ammonia, effluent ammonia, and effluent nitrate data are shown in Figures 4.11, 4.12, and 4.13, respectively. The data indicate that the primary effluent feed was of low strength and that the total nitrogen varied between approximately 15 and 30 mg/L. Ammonia nitrogen varied from 10 to 23 mg/L. Figure 4.10 indicates that the amount of total nitrogen remaining in the effluent varied from zero to about 6 mg/L. Because the Zenon MBR pilot was equipped with an anoxic zone and mixed liquor recycling system, the unit was capable of significant nitrogen removal. However, the degree of nitrogen removal is dependent upon achievement of nitrification prior to denitrification. At various times there was insufficient DO present in the MBRs (due to high TSS concentrations) to allow complete nitrification, and under these conditions, denitrification-based nitrogen removal was reduced. This situation can be observed in Figures 4.12 and 4.13, which show that complete nitrification was achieved approximately 60 to 80% of the time.

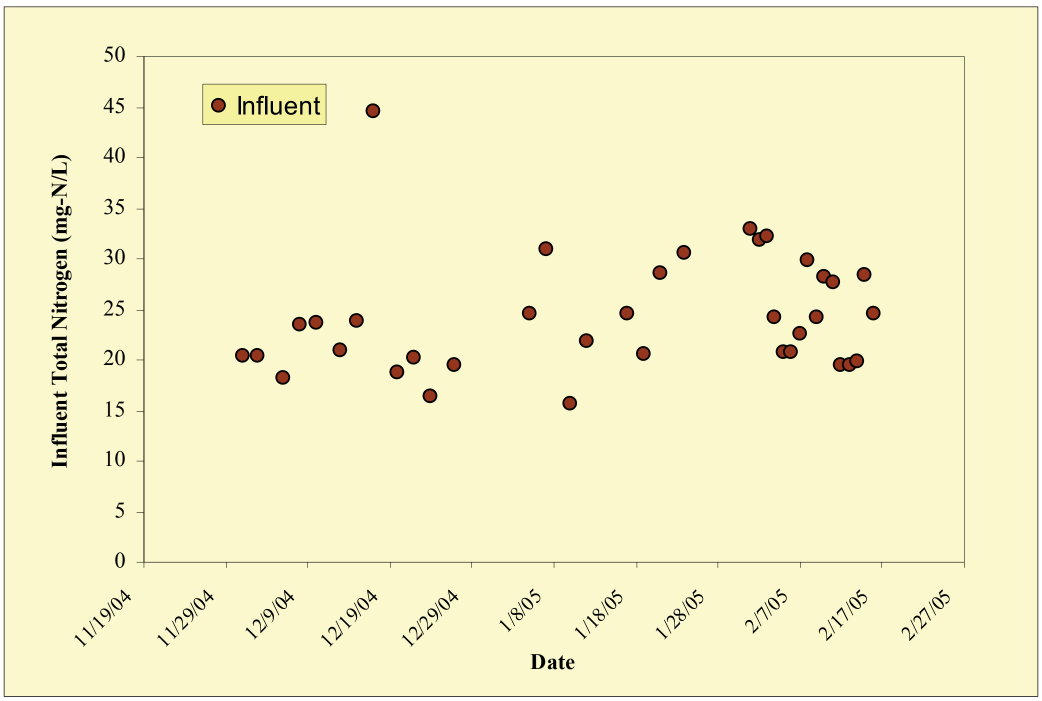

Figure 4.9. Influent total nitrogen concentrations during Phase II (SBWWTP primary effluent).

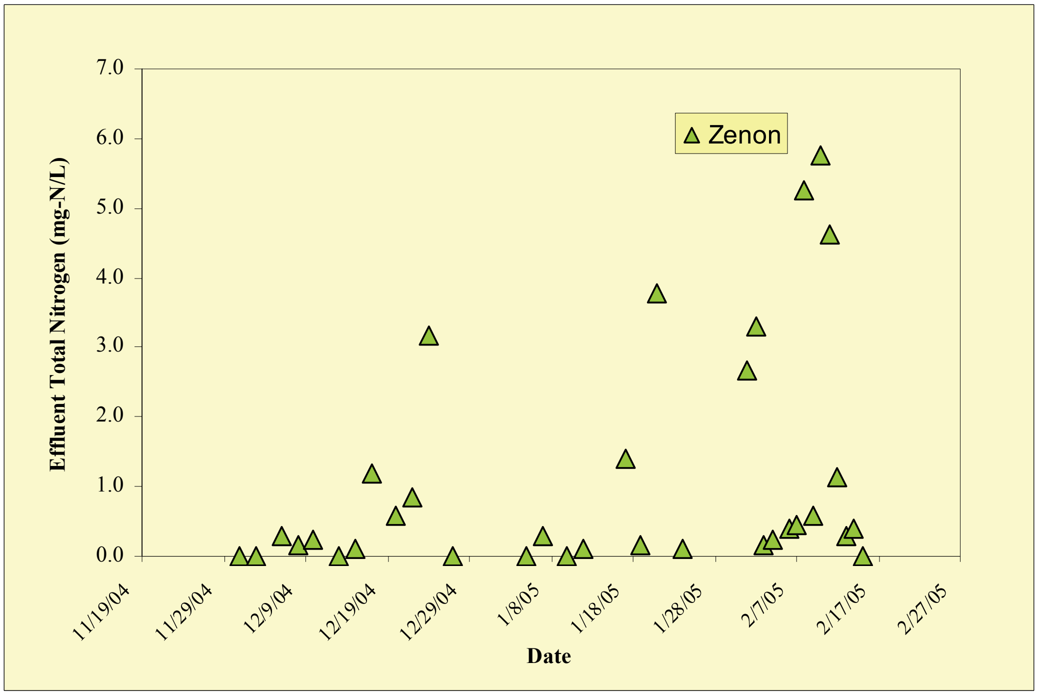

Figure 4.10. Effluent (permeate) total nitrogen during Phase II (SBWWTP primary effluent).

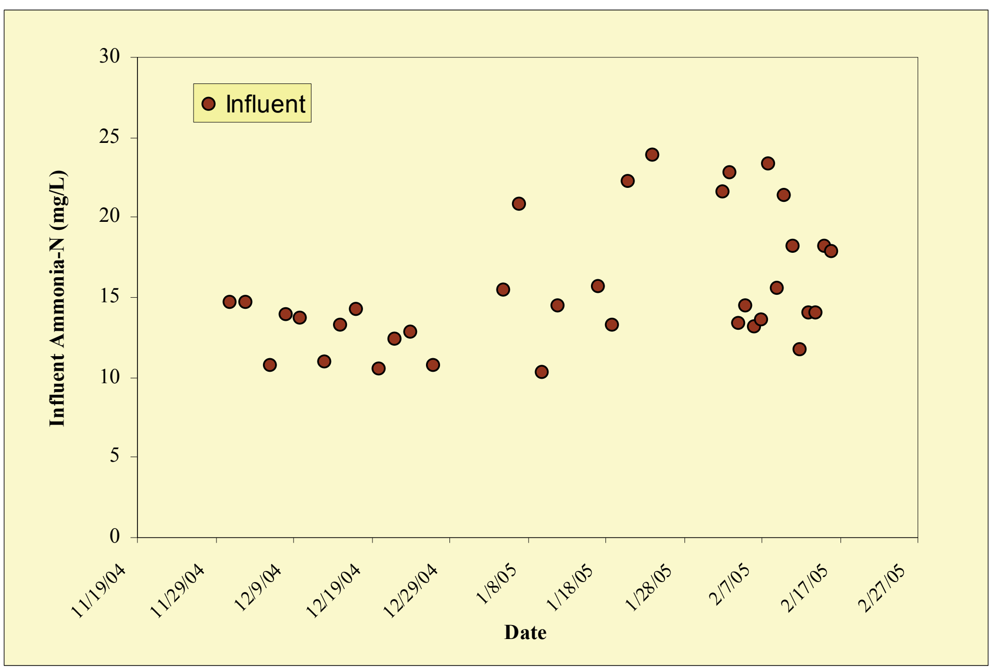

Figure 4.11. Influent ammonia nitrogen during Phase II (SBWWTP primary effluent).

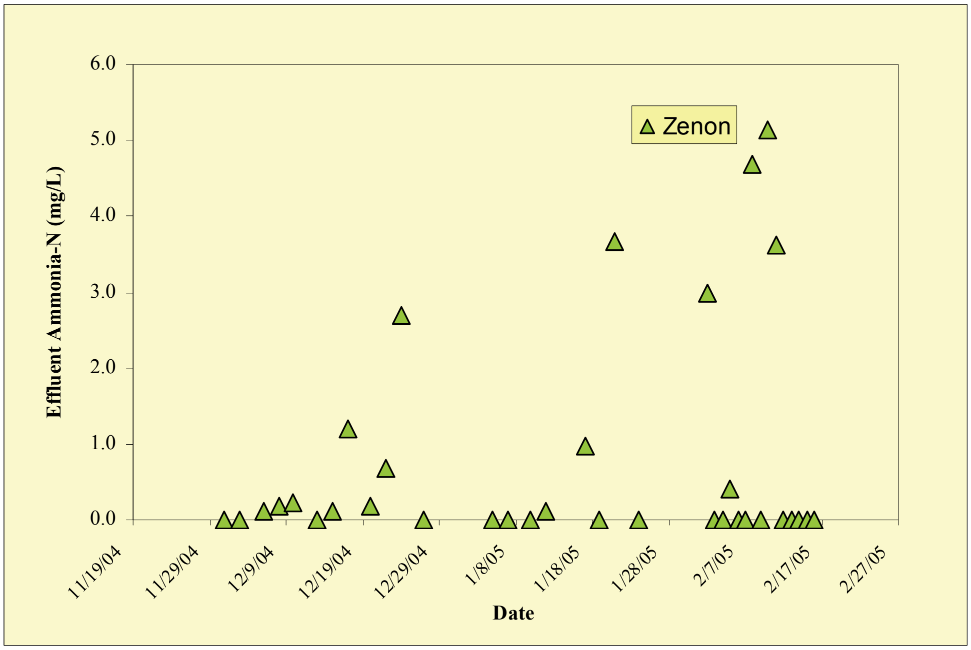

Figure 4.12. Effluent (permeate) ammonia nitrogen during Phase II (SBWWTP primary effluent).

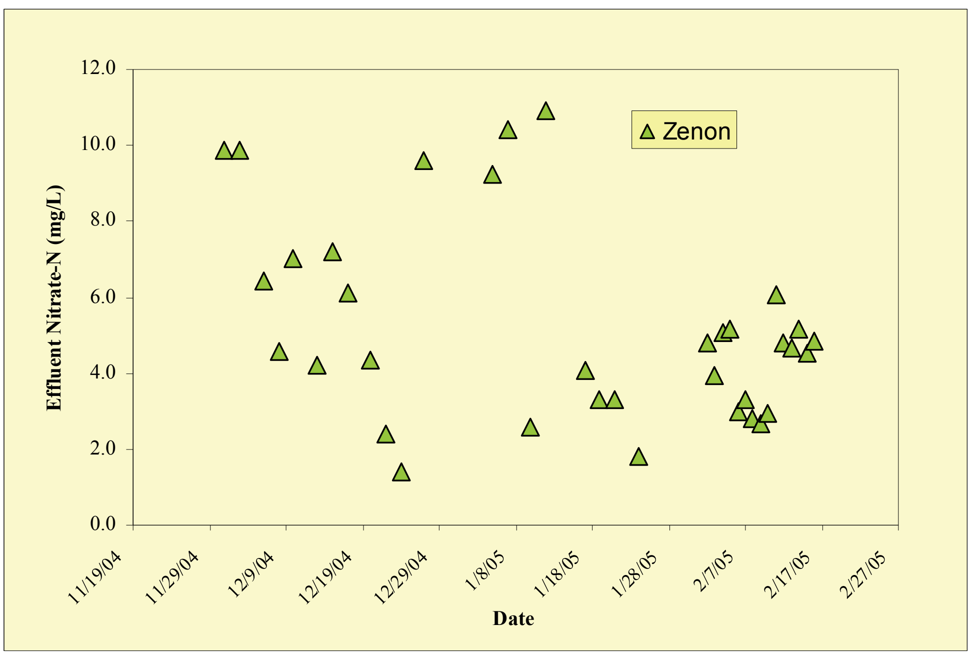

Figure 4.13. Effluent (permeate) nitrate nitrogen during Phase II (SBWWTP primary effluent).

Phosphorus species. Influent and effluent data for total phosphorus are shown in Figures 4.14 and 4.15, respectively. The data indicate that the raw wastewater feed contained between approximately 2.5 and 5 mg of total phosphorus/L. Figure 4.15 shows that effluent total phosphorus varied from about 2 to 5 mg/L. Figure 4.16 indicates that nearly all of the effluent phosphorus was in the form of orthophosphate.

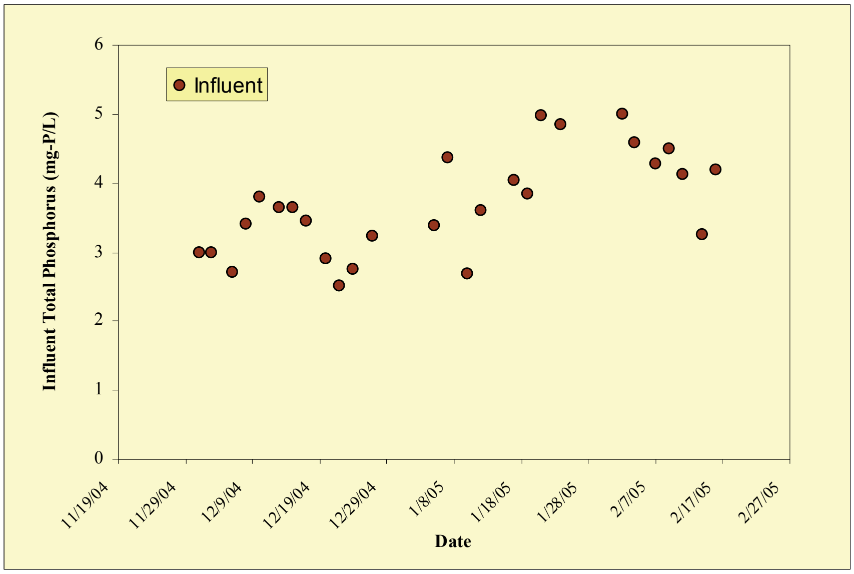

Figure 4.14. Influent total phosphorus during Phase II (SBWWTP primary effluent).

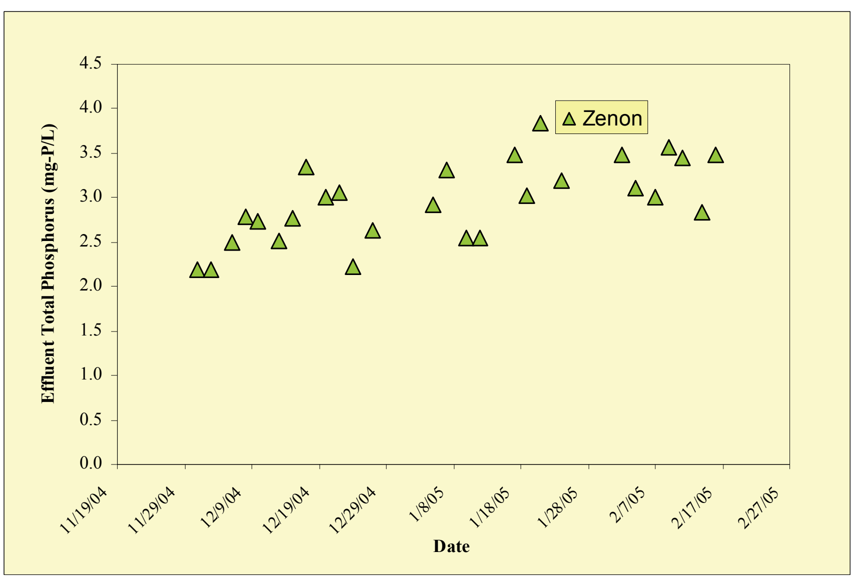

Figure 4.15. Effluent (permeate) total phosphorus during Phase II (SBWWTP primary effluent).

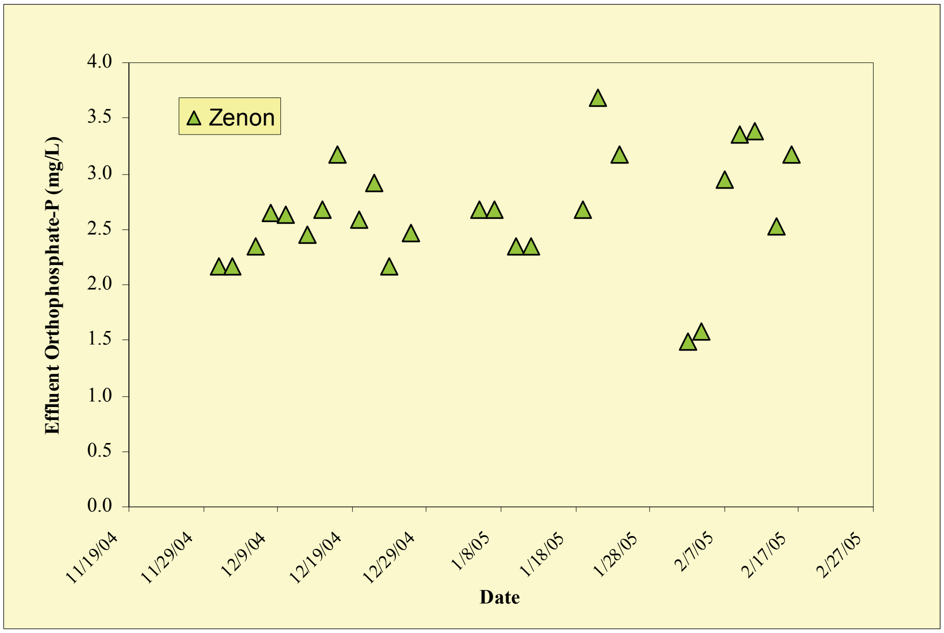

Figure 4.16. Effluent (permeate) orthophosphorus during Phase II (SBWWTP primary effluent).

Turbidity. Effluent data for turbidity are shown in Figure 4.17. The data show the very low values of permeate turbidity that are typical for MBR systems. The figure indicates that all of the turbidity values are less than 0.1 NTU. The turbidity value of 0.2 NTU (achieved 95% of the time) is significant since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, while membrane-filtered effluents require only 80 mW-s/cm^2. Based upon the data in Figure 4.17, the Zenon MBRs would qualify for the reduced UV disinfection dosage.

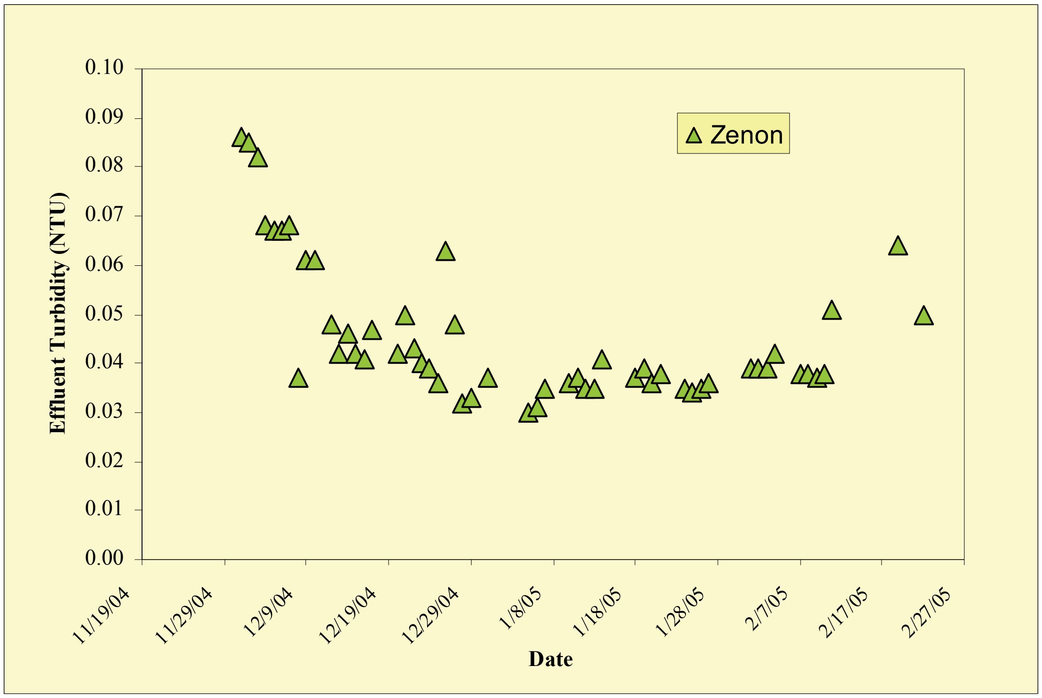

Figure 4.17. Effluent (permeate) turbidity during Phase II (SBWWTP primary effluent).

UVT. Influent UVT_{254} data are shown in Figure 4.18. Figure 4.18 shows the very high values of permeate UVT that are typical for MBR systems. The figure indicates that all of the UVT values are much greater than 65%. The UVT value of 65% is significant since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, whereas membrane-filtered effluents require only 80 mW-s/cm^2. Based upon these data, the Zenon MBR would qualify for the reduced UV disinfection dosage.

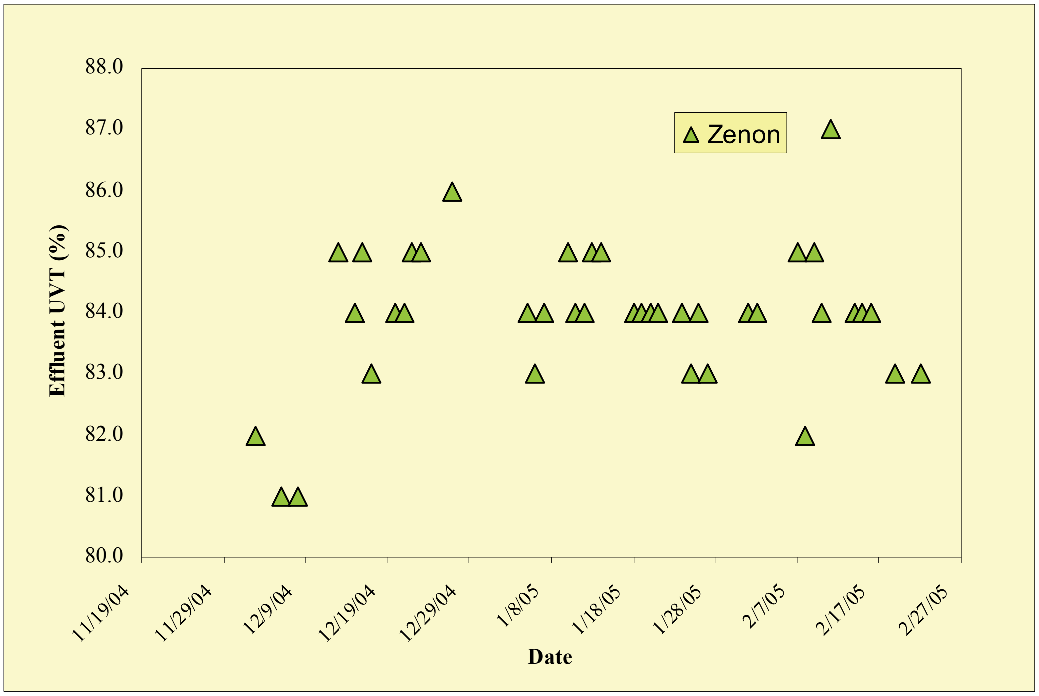

Figure 4.18. Effluent (permeate) UVT_{254} during Phase II (SBWWTP primary effluent).

Fecal coliform and coliphage. Fecal coliform and total coliform were not detected in the effluent from the Zenon MBR during this phase of testing (see Table 4.1). The data indicate one of the great benefits of MBRs, which is that they provide a positive barrier to microbes that are larger than the nominal membrane pore size. Since fecal coliform are about 1.0 µm, they do not pass through to the permeate.

Table 4.1. Effluent fecal coliform and total coliform during Phase II (SBWWTP primary effluent)

Type of Phase II value	Value for:	
	Fecal coliform (CFU/100 mL) in influent	Total coliform (CFU/100 mL) in effluent
Minimum value	<1	<1
Maximum value	<1	<1
Avg. value	<1	<1

pH. Influent and effluent pH data are shown in Figures 4.19 and 4.20, respectively. The data indicate that the pH values of both influent and permeate remained close to 7.0 at all times during the pilot study.

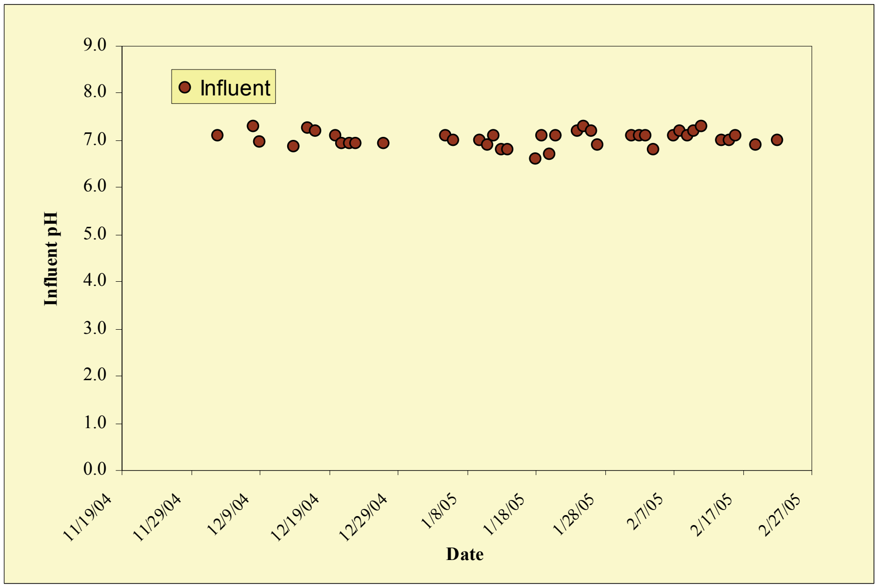

Figure 4.19. Influent pH during Phase II (SBWWTP primary effluent).

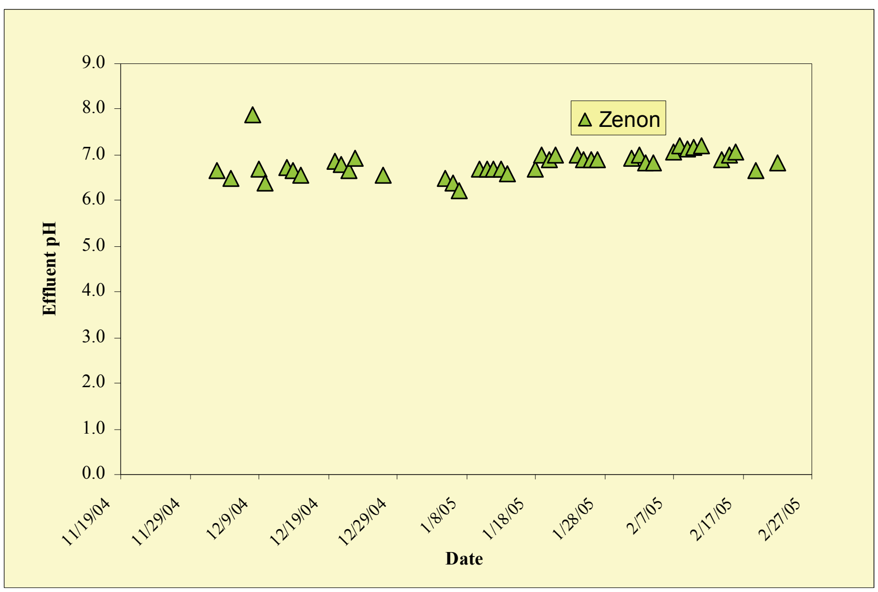

Figure 4.20. Effluent (permeate) pH during Phase II (SBWWTP primary effluent).

Alkalinity. Figures 4.21 and 4.22 show influent and effluent alkalinity data, respectively. The data indicate that alkalinity was sufficient in the primary effluent wastewater and that there was alkalinity remaining in the MBR permeate.

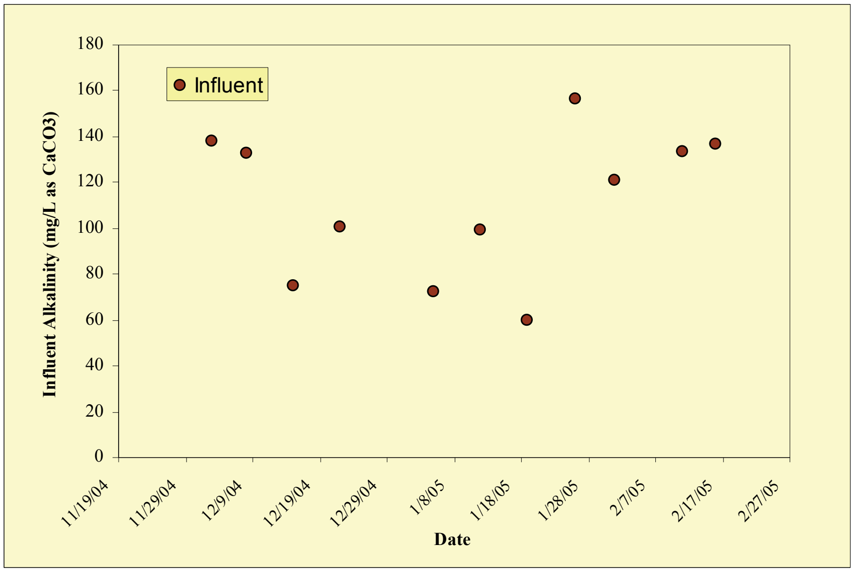

Figure 4.21. Influent alkalinity data for Phase II (SBWWTP primary effluent).

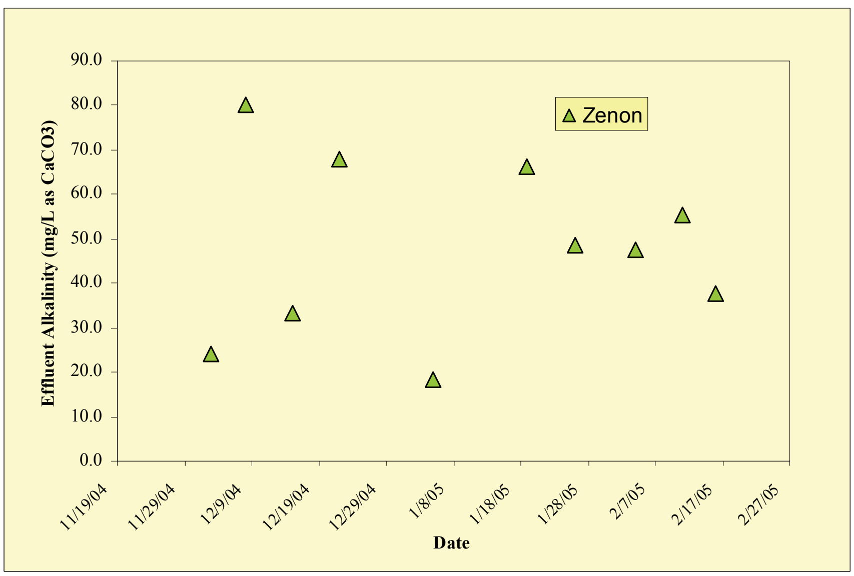

Figure 4.22. Effluent (permeate) alkalinity data for Phase II (SBWWTP primary effluent).

Overall average water quality and removal efficiencies. Table 4.2 gives the overall average values of influent and effluent for all the water quality parameters discussed above. Table 4.2 also shows the average removal efficiencies for the same parameters where appropriate.

Table 4.2. Average water quality data and removal efficiencies (in parentheses) during Phase II (SBWWTP primary effluent)

Analyte	Value for: Influent	Zenon
BOD_5 (mg/L)	69	2.0 (97.1%)
TSS (mg/L)	57	0.07 (99.9%)
COD (mg/L)	190	8.7 (95.4%)
O&G (mg/L)	25.3	2.2
Nitrogen, total (mg of N/L)	24.3	1.1 (95.4%)
Ammonia (mg of N/L)	15.5	0.8
Nitrate (mg of N/L)	NA	5.2
Phosphorus, total (mg of P/L)	3.7	2.0 (20%)
Ortho-phosphorus (mg of P/L)	NA	2.6
UVT_{254} (%)	NA	84
Turbidity (NTU)	NA	0.046
Fecal coliform (CFU/100 mL)	NA	<1
Total coliform (CFU/100 mL)	NA	<1
Alkalinity (mg of $CaCO_3$/L)	111	48 (57%)
pH	7.0	6.8

4.1.2 Wahiawa Pump Station

The goal of this portion of the study was to give the operations staff at the SBWWTP the opportunity to become familiar with how a Zenon satellite treatment system would operate at a remotely located pump station. Zenon sent a new fully containerized MBR treatment unit designed for satellite reclamation studies to Hawaii for this test. The satellite unit was stationed at a pump station located approximately 5 mi from the SBWWTP. A 1.0-mm-pore-size fine screen was used for pretreatment of raw wastewater withdrawn from the pump station wet well in this phase. The Zenon pilot unit was available for testing for only approximately 4 weeks prior to shipping to a mainland location for other scheduled testing. This portion of the Phase II study was conducted from May 23, 2005, to June 20, 2005. The pilot MBR was operated continuously during this period. The main water quality goals were to reduce BOD and TSS to less than 5 mg/L and turbidity to less than 0.2 NTU, keep UVT at greater than 65%, and have <1 fecal coliform CFU/100 mL. There were no nutrient removal goals, and no attempt was made to optimize pilot MBR operations for nutrient removal.

The data are divided into process operating data and water quality data. The process operating data include TMP, MLSSs, and DO concentrations. The water quality data include influent and effluent BOD_5, COD, TSS, total-N, ammonia-N, nitrate-N, total-P, turbidity, UVT_{254}, color, alkalinity, pH, fecal coliform, coliphage, and O&G.

4.1.2.1 Process Operating Data

Table 4.3 shows the process operating data. The Zenon MBR was operated at its design flux of 10 GFD. MBRs are generally operated by maintaining a target MLSS rather than a target SRT. The Zenon pilot unit was operated at an MLSS between 8600 and 9500 mg/L in this portion of the study (see Table 4.3).

Table 4.3. Process operating data during Phase II (Zenon satellite MBR at SBWWTP pump station)

Date	TMP (psi)	MLSS (mg/L)	Flux (gal/ft^2-d)
05/23/05	-2.48	NA	10
05/25/05	-2.51	8,670	10
05/27/05	-2.58	8,780	10
05/30/05	-3.17	8,700	10
06/01/05	-1.20	8,900	10
06/03/05	-3.09	9,120	10
06/08/05	-3.30	9,260	10
06/10/05	-3.53	8,690	10
06/13/05	-3.59	9,310	10
06/17/05	-3.90	8,950	10
06/20/05	-4.03	9,450	10

4.1.2.2 Water Quality Data

The water quality data are presented in Tables 4.4 and 4.5. Due to remoteness, difficulty of access, and the brevity of the period that the equipment was in Hawaii, only approximately 11 sets of samples were obtained for this portion of the study. Overall, the effluent (permeate) water quality produced by the Zenon MBR was excellent by industry standards for secondary effluent and/or filtered secondary (tertiary) effluent. Average influent and effluent values and overall removal efficiencies for all of the water quality parameters are reported in Table 4.6.

BOD. The BOD_5 data indicate that the raw wastewater feed was of medium strength and that the BOD_5 averaged 251 mg/L. Effluent BOD_5 values were all less than 1 mg/L, which is basically undetectable. These permeate concentrations are lower than those collected during earlier operation of the other Zenon pilot unit. This pilot unit was brand-new, and data collection occurred for only a short period during optimal operation. The average BOD_5 removal rate was 99.9%.

COD. The influent COD varied between approximately 463 and 576 mg/L. The MBR permeate contained less than 10 mg of oxygen-demanding materials/L (nearly undetectable). This means that only a tiny amount of soluble organic matter that is not readily degradable as BOD_5 passes through the MBR system. It is often denoted as SMP. Earlier tests with the other Zenon pilot showed similar concentrations of COD passing through the MBR. The average COD removal rate was 99%.

TOC. There are only a few data points available for TOC. The influent data show an average of approximately 100 mg/L, and the effluent averaged less than 10 mg/L. These data also indicate that only a very small amount of soluble organics passed through the pilot unit. The average TOC removal rate was 92.7%.

TSS. The influent TSS data indicate that the raw wastewater feed was of medium strength at an average of 202 mg/L. The effluent data show that all but one of the effluent TSS values were less than the detection limit of 1 mg/L. The TSS removal rate was 100%.

Nitrogen species. The data for total nitrogen indicate that the raw wastewater feed was of medium strength and that concentrations varied between approximately 38 and 53 mg/L. Most of the influent nitrogen was present as ammonia, which varied from 25 to 52 mg/L. No ammonia nitrogen was detected in the effluent, indicating complete nitrification during this study. Effluent nitrate concentrations were quite steady and averaged 16 mg/L, which indicates very good nitrogen removal (65%).

Phosphorus species. Influent and effluent data for total phosphorus data indicate that the raw wastewater feed contained between 3 and 10 mg of total phosphorus/L. Effluent total phosphorus varied from about 1 to 5 mg/L. The average phosphorus removal rate was 33%.

Turbidity. Effluent turbidity values varied from 0.033 to 0.044 NTU. These extremely low values of permeate turbidity are typical for MBR systems. The turbidity value of 0.2 NTU (achieved 95% of the time) is significant since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, while membrane-filtered effluents require only 80 mW-s/cm^2. Based upon the data in Table 4.5, the Zenon MBR permeate would qualify for the reduced UV disinfection dosage.

UVT. Influent UVT_{254} values averaged only 31%, whereas effluent values averaged greater than 80%. Table 4.5 indicates that all of the permeate UVT values are much greater than 65%. The UVT value of 65% is significant since it is the cutoff for membrane-treated effluent intended for unrestricted recycling to qualify for a reduced dosage during UV disinfection based upon NWRI guidelines. Medium-filtered secondary effluent requires a dose of 100 mW-s/cm^2, while membrane-filtered effluents require only 80 mW-s/cm^2. Based upon these data, the Zenon MBR permeate would qualify for the reduced UV disinfection dosage.

Color. The influent in this portion of the study had much color, averaging greater than 300 Pt-Co color units. The effluent had a very low average color content of 20.5 Pt-Co units. The Honolulu BWS has a goal of less than 25 color units for the recycled water that it sells.

Fecal coliform and coliphage. Only one fecal coliform and no coliphage virus were detected in the effluent from the Zenon MBR during this phase of testing (see Table 4.5). The data indicate one of the great benefits of MBRs, which is that they provide a positive barrier to microbes that are larger than the nominal membrane pore size. Since fecal coliform are about 1.0 μm, they generally do not pass through to the permeate. It is not clear that the one detected fecal coliform actually passed through the MBR. More likely, there was contamination of the sample line tap.

pH. Influent pH values were slightly greater than 7.0 at all times during the pilot study. Permeate pH values were somewhat lower, averaging 6.71.

Alkalinity. Tables 4.4 and 4.5 show influent and effluent alkalinity data, respectively. The data indicate that alkalinity was sufficient in the raw wastewater and that there was alkalinity remaining in the MBR permeate.

O&G. Only one set of O&G samples was collected, and the influent value of 46.8 mg/L was typical for raw wastewater. The O&G was not detectable in the permeate sample.

Overall average water quality and removal efficiencies. Table 4.6 gives the overall average values of influent and effluent for all the water quality parameters discussed above. Table 4.6 also shows the average removal efficiencies for the same parameters where appropriate.

Table 4.4. Influent data during Phase II (Zenon satellite MBR at SBWWTP pump station)

Analyte	05/23/05	05/25/08	05/27/05	05/30/05	06/01/05	06/03/05	06/08/05	06/10/05	06/13/05	06/17/05	06/20/05
BOD_5 (mg/L)	NA	430	NA	NA	236	233	162	285	202	235	228
TSS (mg/L)	74	406	105	61	296	276	210	195	174	218	210
COD (mg/L)	NA	NA	NA	NA	NA	576	463	502	514	512	NA
TOC (mg/L)	NA	126	NA	NA	74	NA	99	NA	NA	NA	NA
O&G (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	47	NA	NA
Nitrogen, Total (mg N/L)	38	43	44	48	51	51	46	42	44	53	48
Ammonia (mg N/L)	38	26	44	43	48	43	34	33	39	52	36
Nitrate (mg N/L)	<0.1	<0.1	<0.1	<0.1	<0.1	6.2	<0.1	<0.1	<0.1	<0.1	<0.1
Phosphorus, Total (mg P/L)	7.0	7.2	6.1	6.9	7.5	3.4	3.2	3.1	7.1	10.1	7.5
UVT_{254} (%)	26	26	29	31	38	32	36	25	28	30	36
Color (Pt-Co units)	396	398	322	316	219	288	273	394	336	268	300
Fecal Coliform (CFU/100mL)	3.2 x 10E6	2.8 x 10E6	NA	3.9 x 10E6	2.8 x 10E6	NA	5.9 x 10E6	NA	3.4 x 10E6	NA	2,9 x 10E6
Fecal Coliphage (CFU/100mL)	NA	2.4 x 10E5	NA	NA	1.2 x 10E5	NA	4.8 x 10E5	NA	NA	NA	NA
Alkalinity (mg $CaCO_3$/L)	NA	NA	NA	NA	NA	NA	NA	190	NA	NA	NA
pH	6.87	6.84	7.24	7.19	7.19	7.25	7.04	7.11	6.75	7.02	7.07

Table 4.5. Effluent (permeate) data during Phase II (Zenon satellite MBR at SBWWTP pump station)

Analyte	05/23/05	05/25/08	05/27/05	05/30/05	06/01/05	06/03/05	06/08/05	06/10/05	06/13/05	06/17/05	06/20/05
BOD_5 (mg/L)	NA	0.4	NA	NA	<0.1	0.3	0.4	0.4	0.3	0.1	<0.1
TSS (mg/L)	<0.1	<0.1	<0.1	NA	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2
COD (mg/L)	NA	0.8	1.6	NA	1.4	7.6	9.8	8.7	5.7	5.3	NA
TOC (mg/L)	NA	3.1	NA	NA	2.4	NA	16.4	NA	NA	NA	NA
O&G (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	<1.0	NA	NA
Nitrogen, Total (mg N/L)	17.1	18.5	17.2	15.1	16.0	12.8	17.7	16.0	17.0	15.2	13.8
Ammonia (mg N/L)	<0.1	<0.1	<0.1	NA	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Nitrate (mg N/L)	17.1	18.5	17.2	15.1	16.0	12.8	17.7	16.0	17.0	15.2	13.8
Phosphorus, Total (mg P/L)	4.4	4.5	4.4	4.2	5.4	1.4	4.2	4.6	4.8	4.2	4.3
Turbidity (NTU)	0.042	0.040	0.041	0.040	NA	0.044	0.035	0.036	0.036	0.034	0.033
UVT_{254} (%)	81	81	84	81	83	82	81	82	82	86	83
Color (Pt-Co units)	16	18	21	22	25	21	18	23	22	22	18
Fecal Coliform (CFU/100mL)	<1	<1	<1	<1	<1	NA	1	NA	<1	NA	<1
Fecal Coliphage (CFU/100mL)	<1	<1	<1	<1	<1	NA	<1	NA	NA	NA	NA
Alkalinity (mg $CaCO_3$/L)	NA	NA	NA	NA	NA	NA	NA	44	NA	NA	NA
pH	6.74	6.85	6.89	6.92	6.65	6.74	6.62	6.58	6.53	6.57	6.67

Table 4.6. Average water quality data and removal efficiencies (in parentheses) during Phase II (Zenon satellite MBR at SBWWTP pump station)

Analyte	Value for:	
	Influent	Zenon
BOD_5 (mg/L)	251	0.2 (99.9%)
TSS (mg/L)	202	<0.1 (100%)
COD (mg/L)	513	5.1 (99.0%)
TOC (mg/L)	99.6	7.3 (92.7%)
O&G (mg/L)	46.8	<1.0 (100%)
Nitrogen, total (mg of N/L)	46.1	16.0 (65%)
Ammonia (mg of N/L)	39.5	<0.1
Nitrate (mg of N/L)	NA	16.0
Phosphorus, total (mg of P/L)	6.3	4.2 (33%)
UVT_{254} (%)	30.5	82.3
Turbidity (NTU)	NA	0.038
Fecal coliform (CFU/100 mL)	3.6×10^6	<1 (6 log)
Total coliform (CFU/100 mL)	2.8×10^5	<1 (5 log)
Alkalinity (mg of $CaCO_3$/L)	190	44 (77%)
pH	7.05	6.71

4.2 EVALUATION OF ENVIROQUIP MEMBRANE THICKENER/DIGESTER

4.2.1 Background and Chronology

In this phase of the study, we investigated the potential utility of MBR technology for thickening and aerobic digestion of secondary sludge. The use of MBRs for thickening is an even newer concept than is MBR treatment of wastewater. Several such systems are in operation in Europe, Japan, and the United States. However, all of the existing systems are used to thicken waste sludge from MBR treatment systems, which generally have SRTs in excess of 15 days. The main goals for this phase of the study were to maximize the thickening of 5-day SRT secondary sludge (at least 3% solids but up to perhaps 6% or higher) while simultaneously providing digestion (38% volatile-solid reduction for Class B biosolids) and to minimize BOD and ammonia in the permeate.

The Enviroquip pilot MBR unit was retrofitted or converted into a PAD-K thickener/digester, and operations commenced on May 4, 2005. For thickening, the membranes are operated at only 5 GFD (1/3 of MBR), at double the aeration rate of MBR, and at a normal relax cycle time of 9 min of permeation and 1 min of relax. A feed system failure on May 14 and 15, 2005 (inlet valve stuck open), caused the unit to fill up and overflow. The problem was corrected, and the system level returned to normal by draining, which had the effect of diluting the solids in the system from about 20,000 mg/L to 13,000 mg/L. Another failure of the feed system on May 28 and 29, 2005 (feed pump burnout), caused the unit to thicken all of the solids present in the system to about 60% of the total volume. This caused significant fouling of the membranes and their automatic shutdown (due to a TMP that was > −3 psi). The system was diluted with water and aerated for several days until a new pump could be obtained and the membranes cleaned (bleaching at 1000 ppm inside the membranes for 2 h in situ) on June 3, 2005. The membranes fouled again within a few days, and we had problems again with the feed pump system, which were not adequately corrected until August 24, 2005. The membrane panels were physically cleaned by removing each one and spraying off the accumulated cake layer on August 11, 2005. When the feed was restarted on August 24, 2005, the membranes fouled within 4 days. The system was operated in intermittent mode (intermittent aeration without feed or permeation) until October 5, 2005, when the tanks were drained, the MBT filled with clean water, and the membranes cleaned (bleaching at 1000 ppm inside the membranes for 2 h in situ). The unit was restarted by filling with feed sludge on October 7, 2005. The TSS started at 3667 and increased to 38,880 by November 16, 2005. At that point, the TMP exceeded −3 psi and the unit stopped permeating. The unit was then operated in intermittent mode until December 7, 2005, to see what would happen. The unit was placed back in permeate mode on December 7, 2005, but TMP exceeded –3 psi by December 12, 2005, when operations ceased. Data collected on SMP and (EPS have revealed that the SMP values rapidly increase to more than 10 times greater than that in other operating MBRs. The SMP is believed to be the cause of the membrane fouling. In addition, ammonia increases rapidly, perhaps causing toxicity. The short-sludge-age feed that contains significant nitrogen and volatile solids is more difficult to treat with the PAD-K system than are "older" sludges normally treated in such systems.

4.2.2 Operational and Water Quality Data

Results of the pilot study on thickening and digestion of TSS and VSS in the feed sludge (TF/SC waste sludge) are presented in the figures below. Figure 4.23 shows the concentrations of TF/SC. Figure 4.24 shows the concentrations of mixed liquor solids. It was calculated that the feed TSS averages 3984 mg/L and that the feed was 87.8% volatile on average. The mixed liquor is 79.9% volatile solids on average. The calculated average volatile-solid reduction for the whole study period was 45%. This is somewhat better than the goal of 38%. There was no sludge wasting during this study. It was possible to thicken the solids up to approximately 4%; however, continuous operation at elevated solid concentrations was not achieved. The plan was to thicken up the solids at a high rate to 3% and then begin solid wasting to give an SRT of 28 days. However, each time that this was attempted, membrane fouling caused excessive TMP increases that prevented continuous operations (Figure 4.44). From May 4 to June 3, the thickener was in permeation mode (with full aeration) for 18 h/day, which gave a hydraulic retention time (HRT) of 6.1 days. In order to improve volatile-solid reduction and nitrification, the permeate time was reduced to 8 h/day (HRT = 13.7 days) and the aeration schedule was also increased. On October 7, the aeration schedule was again increased such that the digester was aerated continuously. Figure 4.25 shows the DO concentration in the MBT, which indicates that there was sufficient air to keep it aerobic; however, higher DO concentrations might be necessary in order to achieve full nitrification.

Figures 4.26, 4.27, 4.28, and 4.29 show the mixed liquor, influent, and effluent nutrient concentrations. Figure 4.26 shows that, during the 3rd week and again after each time that the TSS was allowed to build up (August 1 to September 2 and October 7 to November 7), the nitrogen concentrations rapidly increased. Figure 4.29 indicates that the nitrogen increase was due to ammonia, which increased to as high as 230 mg/L, a level considered toxic (nitrification poisoning). In order to maintain nitrification and reasonable ammonia concentrations, sufficient alkalinity, aeration, and retention time are required. Figure 4.35 indicates that, for the most part, pH was maintained at reasonable values in this study. Other limited data indicate that sufficient alkalinity was present and that there was residual alkalinity in the process permeate. This finding indicates that the important issue is retention time. Apparently, additional time is required to fully oxidize all of the nitrogen in the “young” TF/SC sludge. Figures 4.30 and 4.31 show permeate UVT_{254} and color, respectively. These data indicate that the PAD-K permeate had a light brownness that adsorbed UV light and that when the unit started to lose nitrification the color/UVT worsened. Figures 4.32, 4.33, and 4.34 show permeate BOD, TOC, and turbidity, respectively. These data indicate that permeate BODs varied between 2 and 14 mg/L, that turbidities varied between less than 0.2 and 1.6 NTU, and that permeate TOC steadily increased from 3 to 21 mg/L during the last system restart. Figures 4.32, 4.33, and 4.34 also indicate that, when the unit started to lose nitrification, the BOD, TOC, and turbidity worsened.

Figures 4.36 through 4.43 show data on SMP and EPS. During the last restart, the carbohydrate SMP increased the most dramatically (from approximately 20 to approximately 200 mg/L). While the carbohydrate EPS went up greatly (from 36 to 160 mg/L), as did the protein SMP (from <1 to 10 mg/L), the protein EPS did not change very much (from 25 to 30 mg/L). The most important is the SMP, which can foul the membranes by blocking membrane pores. Figure 4.38 and 4.40 show somewhat of a correlation between MLSS and carbohydrate SMP and ammonia, respectively. Figure 4.39 shows no such correlation for protein SMP. Figures 4.41 and 4.42 show some correlation between TMP and protein SMP, carbohydrate SMP, and possibly carbohydrate EPS. Figure 4.43 shows a good correlation between permeate TOC and SMP concentrations. These data indicate that carbohydrate microbial products and, to a slightly lesser extent, protein products were elevated when the membranes approached a fouled state. In addition, it appears that the production of excessive extracellular products could be a biological response to the presence of excess ammonia. This finding highlights the importance of maintaining acceptable biological conditions such that the membrane, biofilm, or cake layer can function optimally for biofiltration.

Additional aeration time was implemented (as described above) to improve nitrification; however, it was inadequate. Apparently, additional retention time at the higher aeration rates would be required in order to maintain continuous full nitrification for this type of waste sludge. The buildup of ammonia, the consequent nitrification poisoning, and associated enhanced SMP and EPS production that caused membrane fouling were due to the very high nitrogen content of the "young" TF/SC sludge utilized in this study. It is noteworthy that, when allowed to operate in intermittent mode for a period of time, the PAD-K system seemed to recover from the ammonia poisoning, indicating that batch or even semicontinuous operation could be achieved with this type of waste stream.

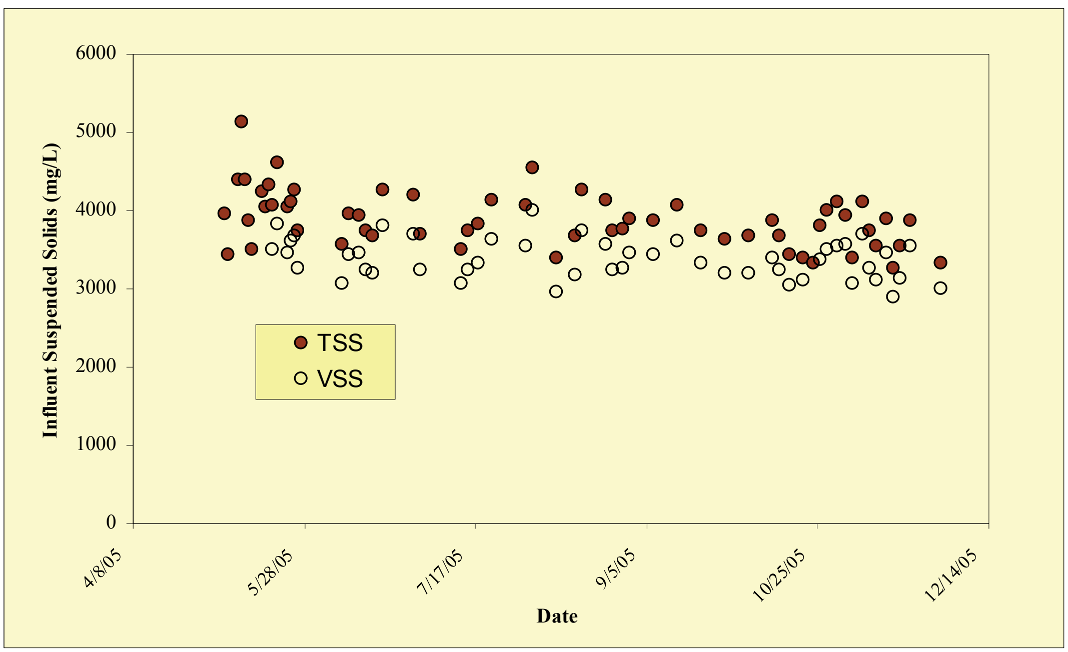

Figure 4.23. Influent suspended solids during thickening/digestion study using Enviroquip PAD-K system.

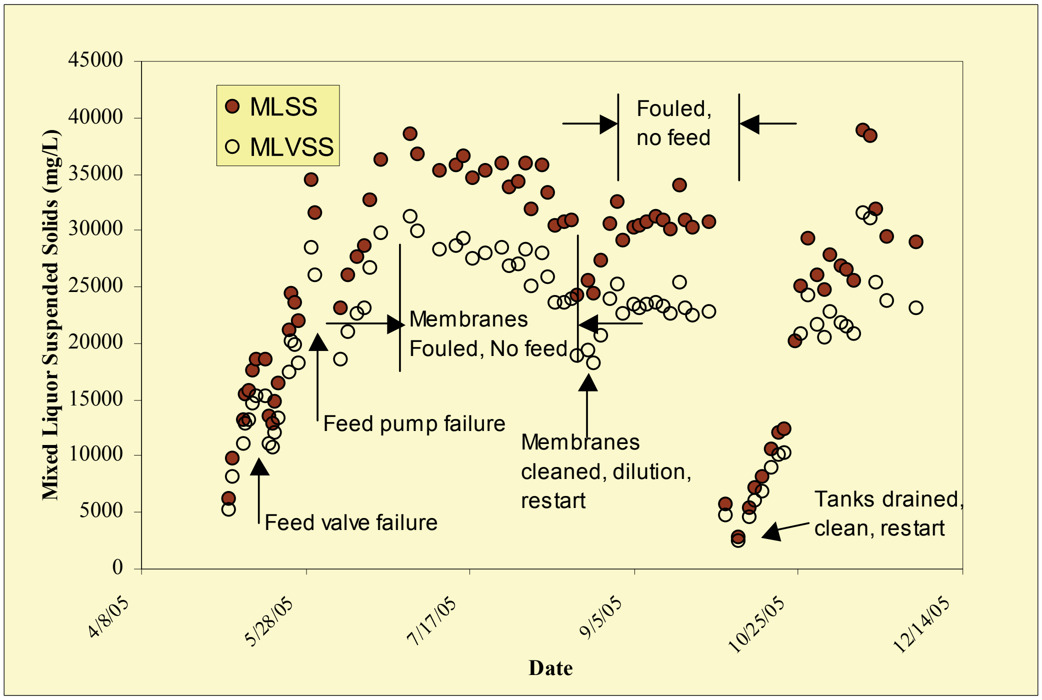

Figure 4.24. MLSSs during thickening/digestion study using Enviroquip PAD-K system.

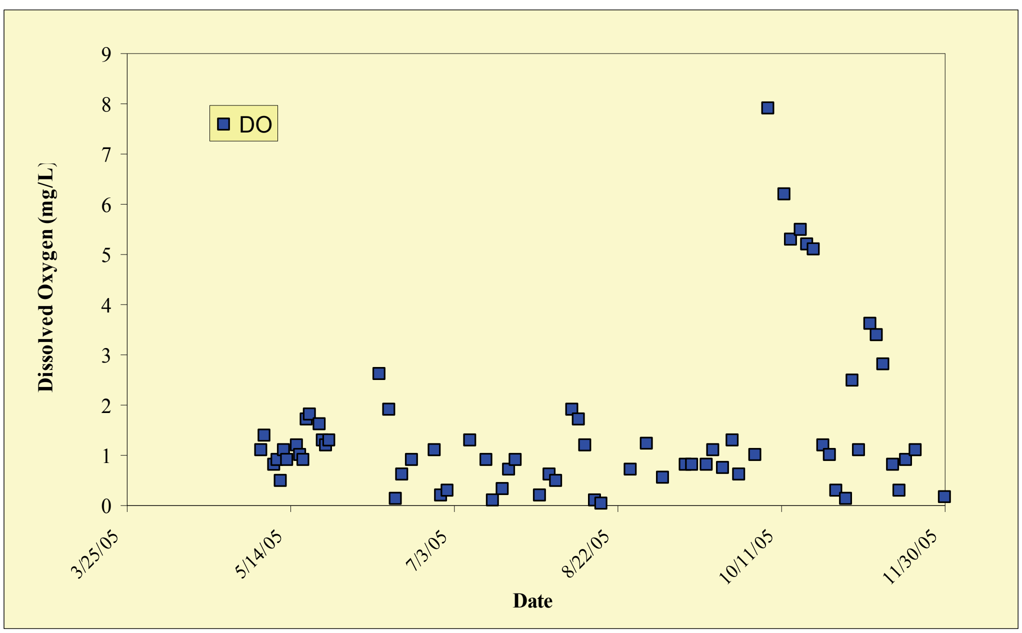

Figure 4.25. MBT DO during thickening/digestion study using Enviroquip PAD-K system.

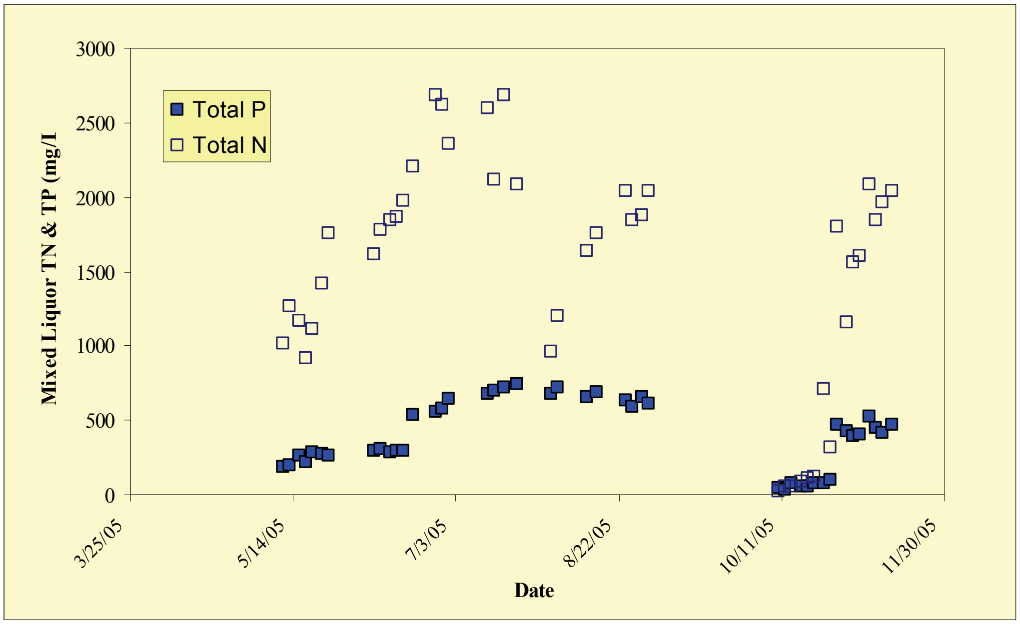

Figure 4.26. Mixed liquor nitrogen and phosphorus during thickening/digestion study using Enviroquip PAD-K system.

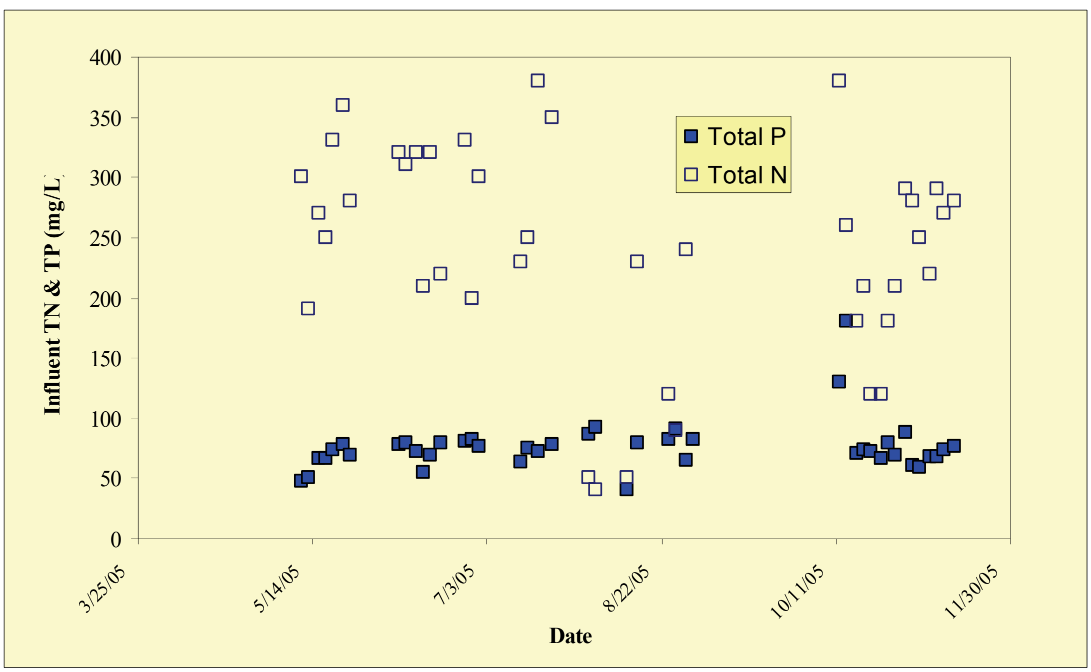

Figure 4.27. Influent nitrogen and phosphorus during thickening/digestion study using Enviroquip PAD-K system.

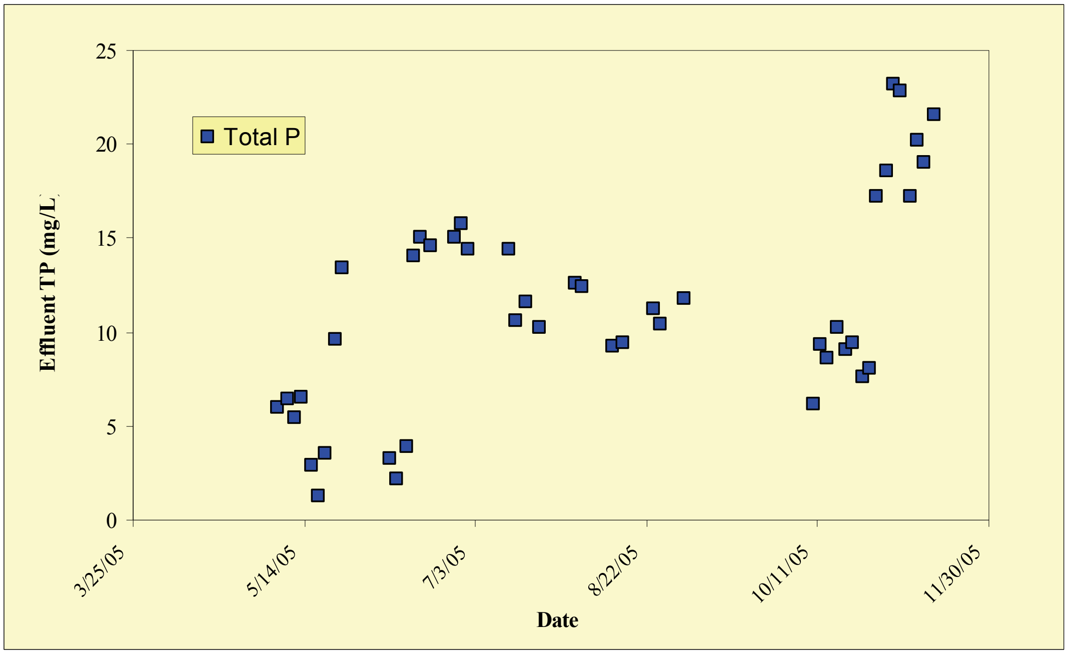

Figure 4.28. Effluent (permeate) phosphorus during thickening/digestion study using Enviroquip PAD-K system.

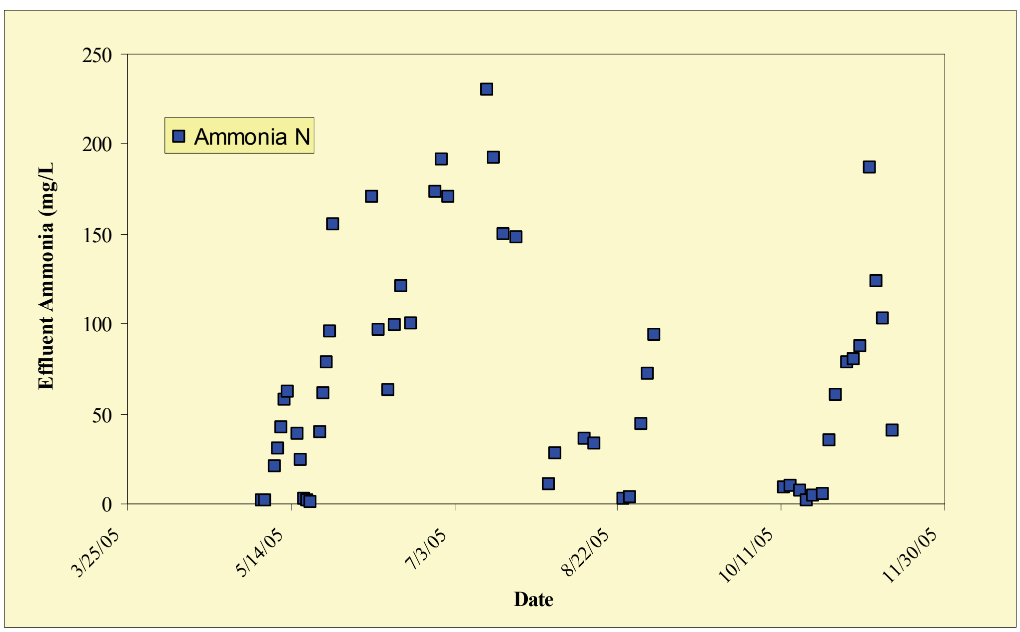

Figure 4.29. Effluent (permeate) ammonia nitrogen during thickening/digestion study using Enviroquip PAD-K system.

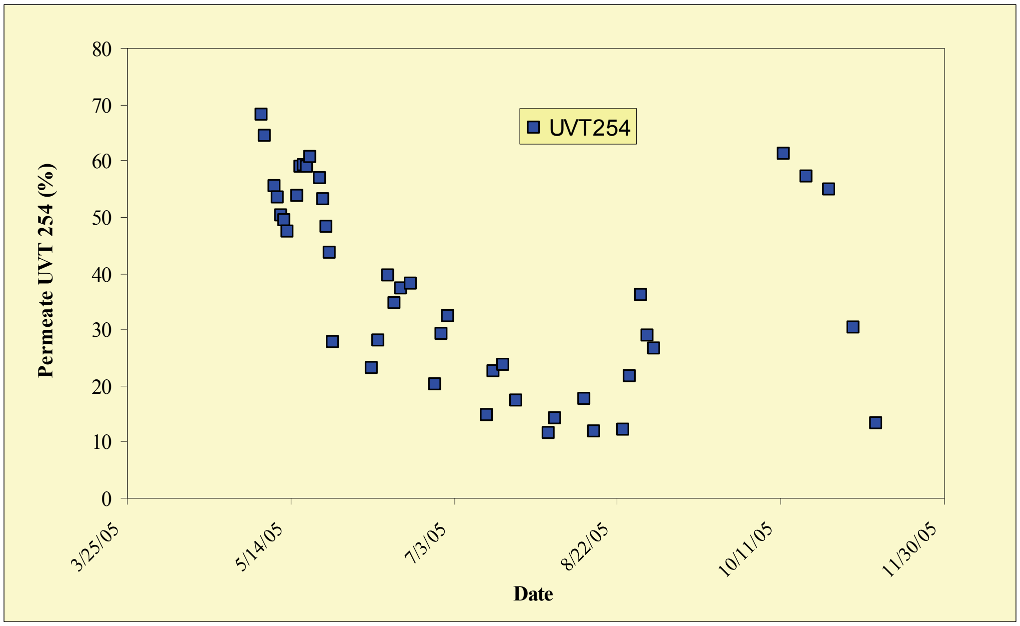

Figure 4.30. Effluent (permeate) UVT during thickening/digestion study using Enviroquip PAD-K system.

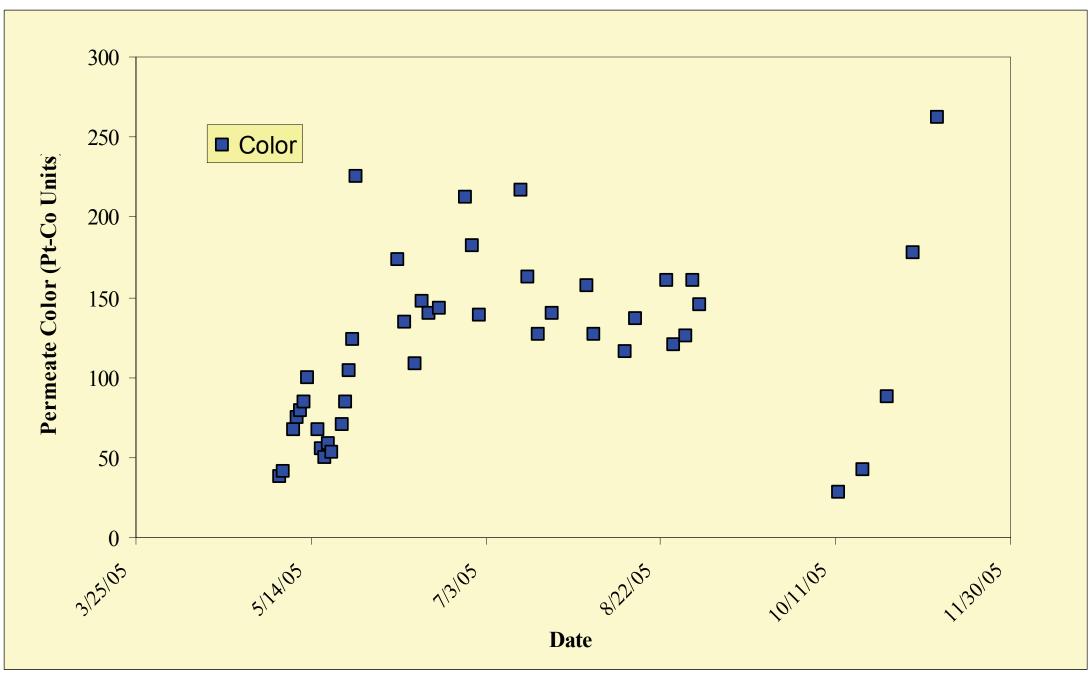

Figure 4.31. Effluent (permeate) color during thickening/digestion study using Enviroquip PAD-K system.

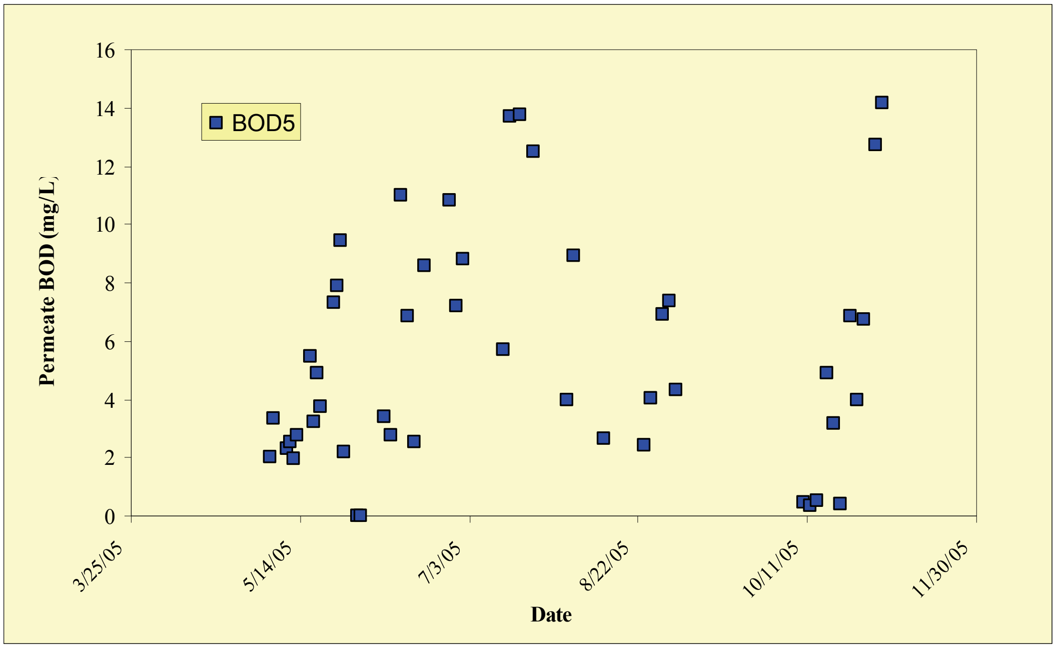

Figure 4.32. Effluent (permeate) BOD during thickening/digestion study using Enviroquip PAD-K system.

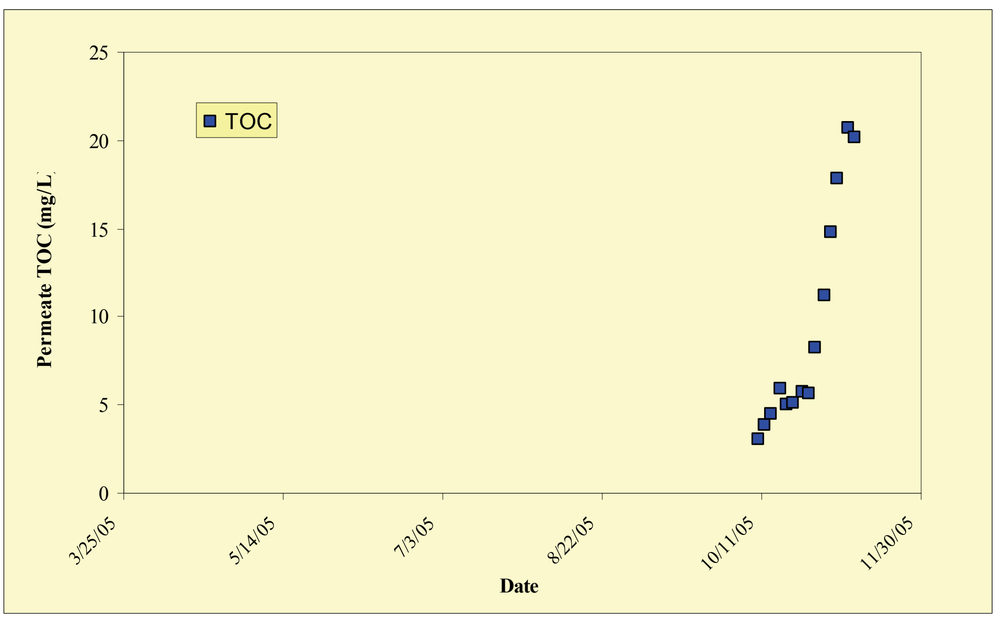

Figure 4.33. Effluent (permeate) TOC during thickening/digestion study using Enviroquip PAD-K system.

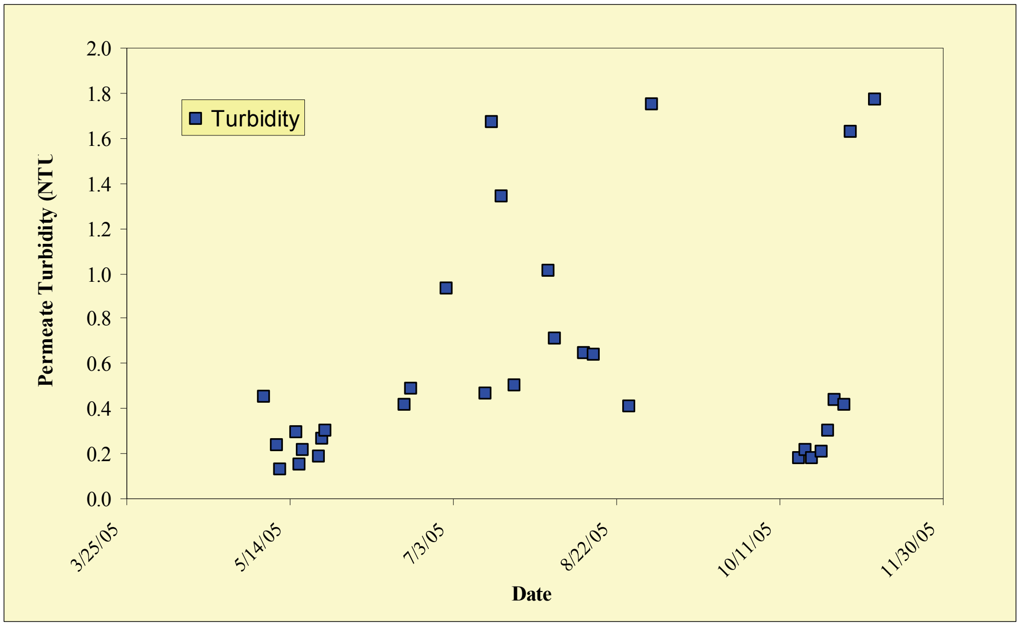

Figure 4.34. Effluent (permeate) turbidity during thickening/digestion study using Enviroquip PAD-K system.

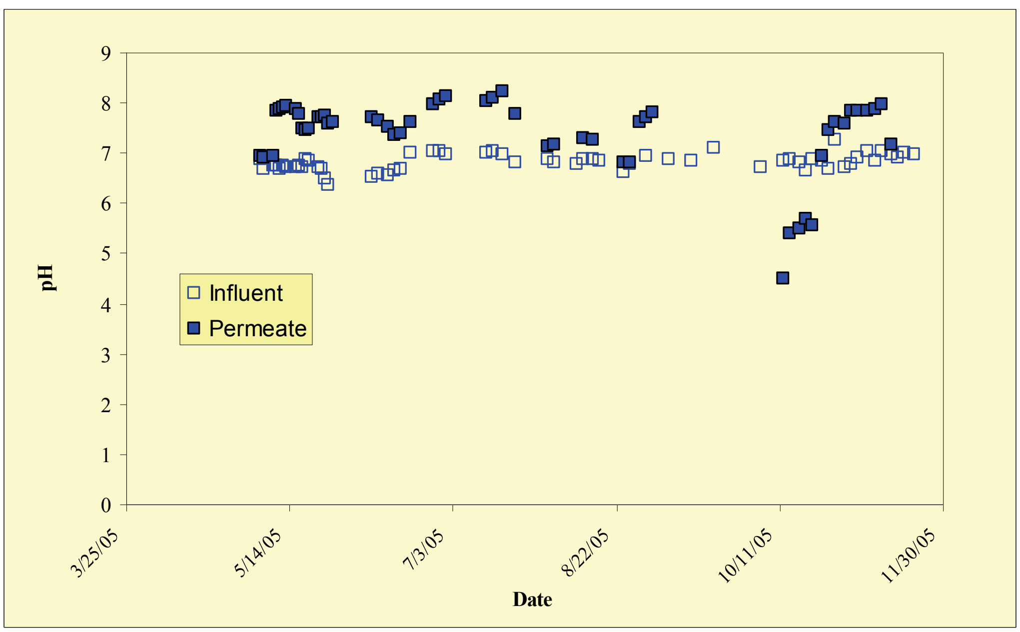

Figure 4.35. Effluent (permeate) pH during thickening/digestion study using Enviroquip PAD-K system.

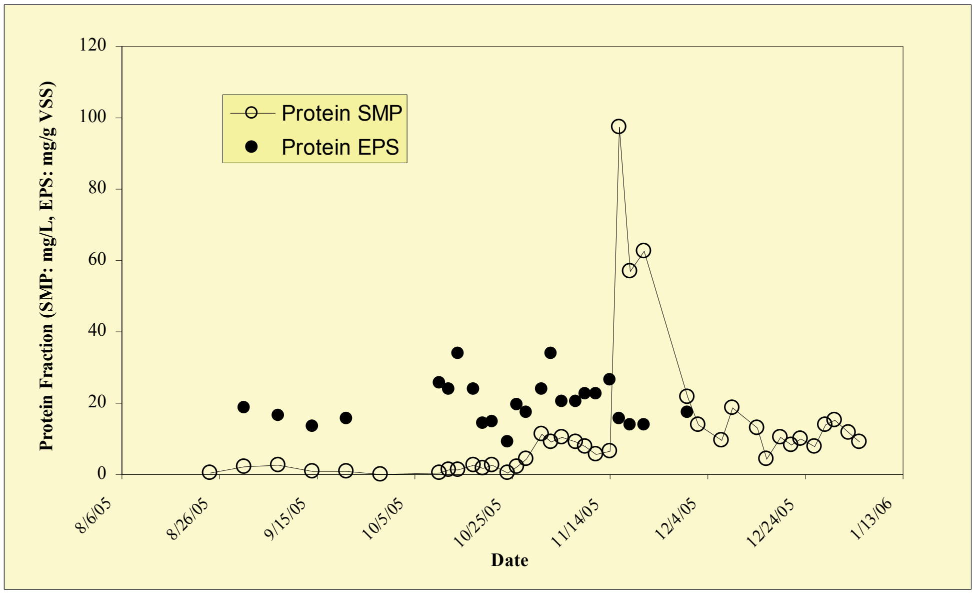

Figure 4.36. Mixed liquor protein fractions during thickening/digestion study using Enviroquip PAD-K system.

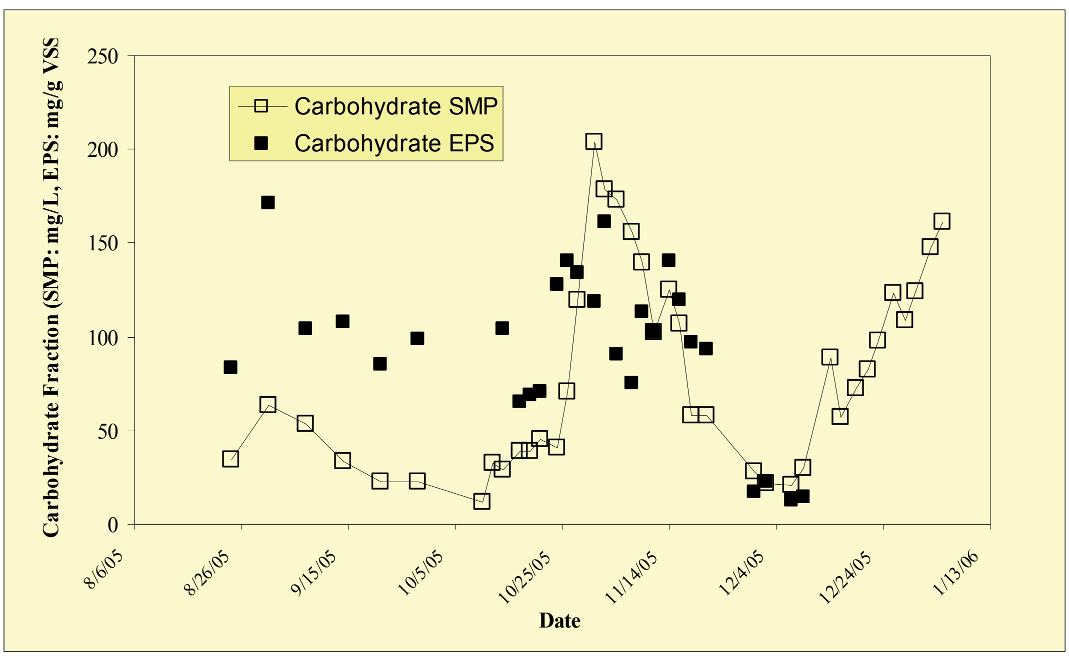

Figure 4.37. Mixed liquor carbohydrate fractions during thickening/digestion study using Enviroquip PAD-K system.

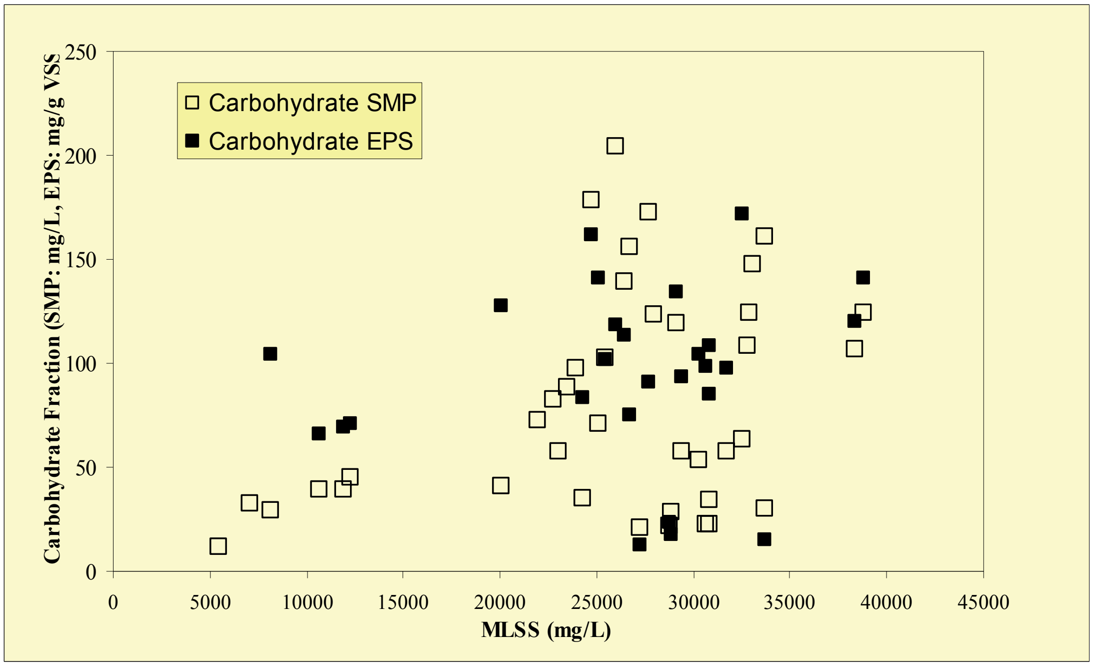

Figure 4.38. Mixed liquor carbohydrate fractions as a function of MLSS during thickening/digestion study using Enviroquip PAD-K system.

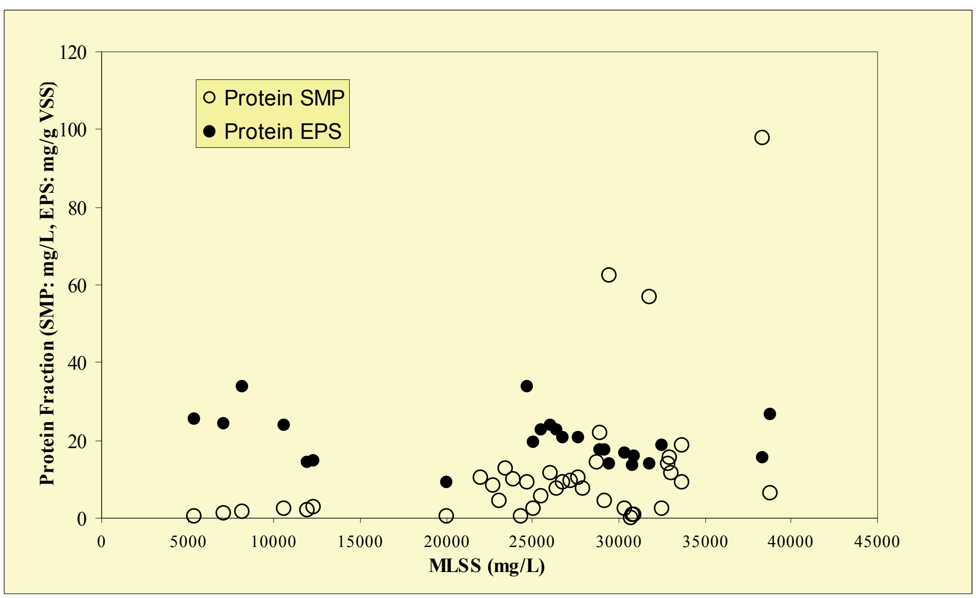

Figure 4.39. Mixed liquor protein fractions as a function of MLSS during thickening/digestion study using Enviroquip PAD-K system.

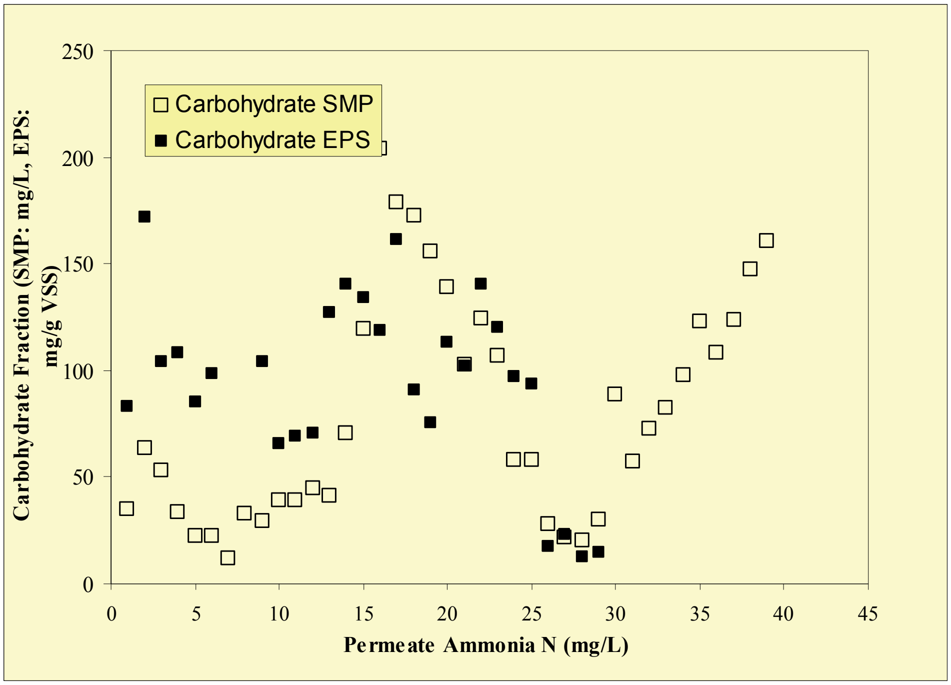

Figure 4.40. Permeate ammonia-N as a function of MLSS during thickening/digestion study using Enviroquip PAD-K system.

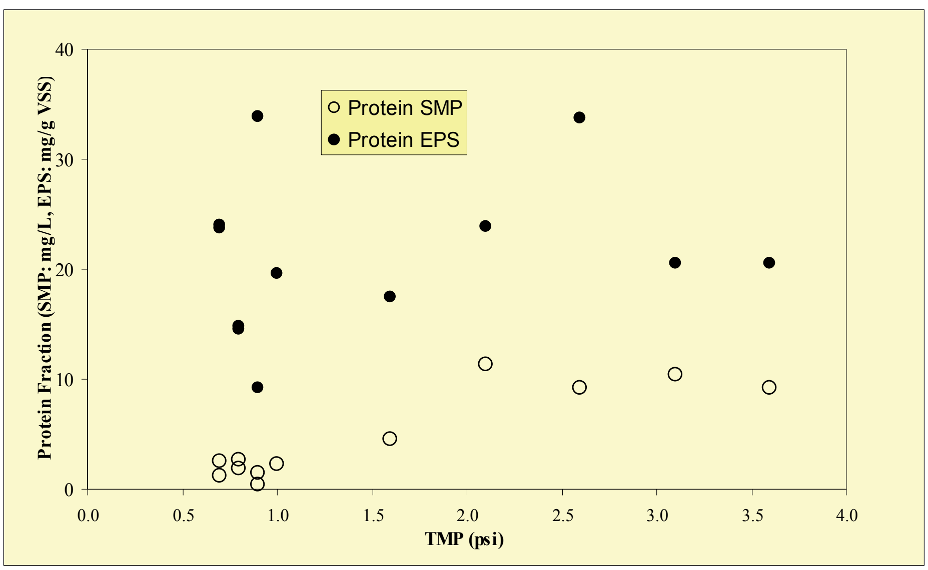

Figure 4.41. Mixed liquor protein fractions as a function of TMP during thickening/digestion study using Enviroquip PAD-K system.

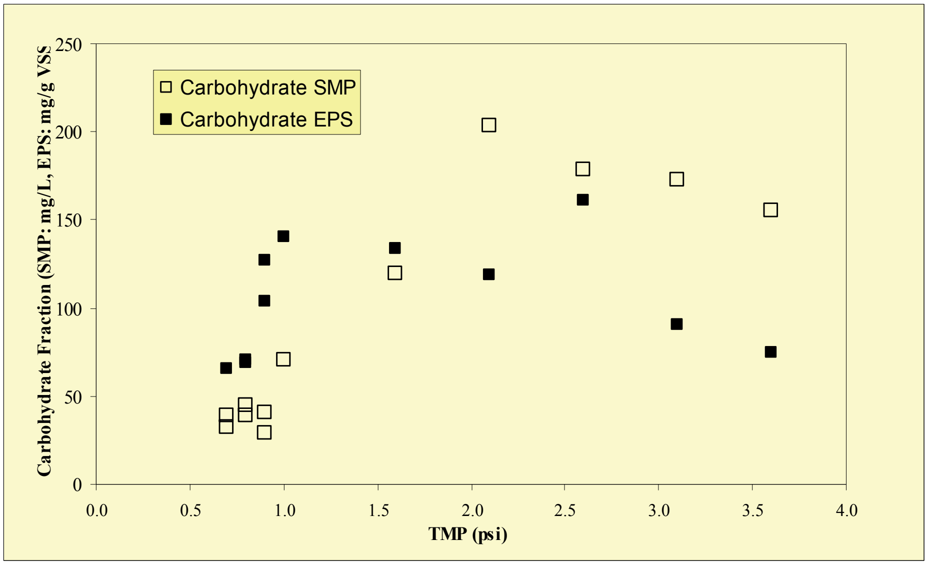

Figure 4.42. Mixed liquor carbohydrate fractions as a function of TMP during thickening/digestion study using Enviroquip PAD-K system.

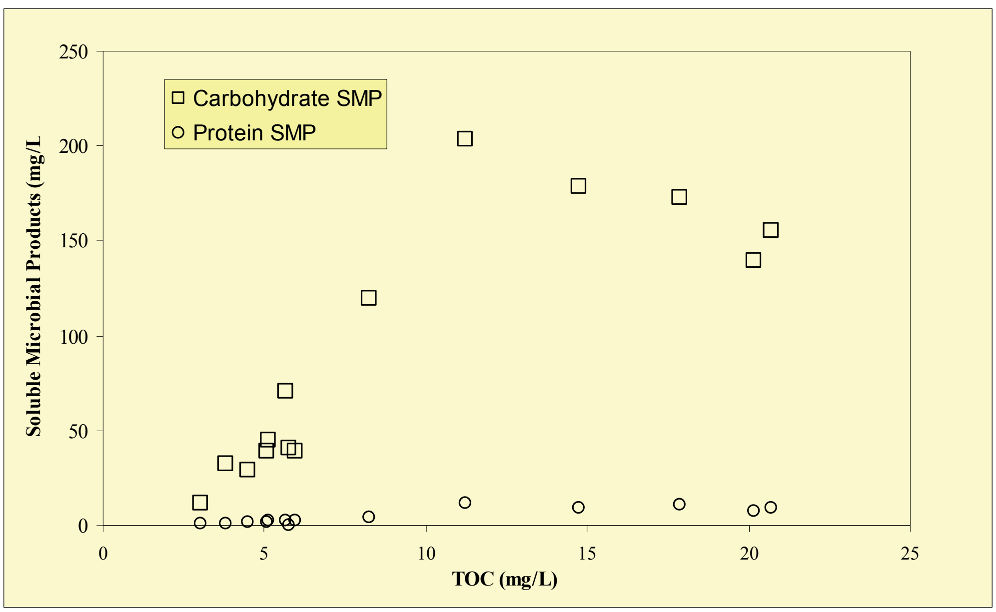

Figure 4.43. Permeate SMP as a function of permeate TOC during thickening/digestion study using Enviroquip PAD-K system.

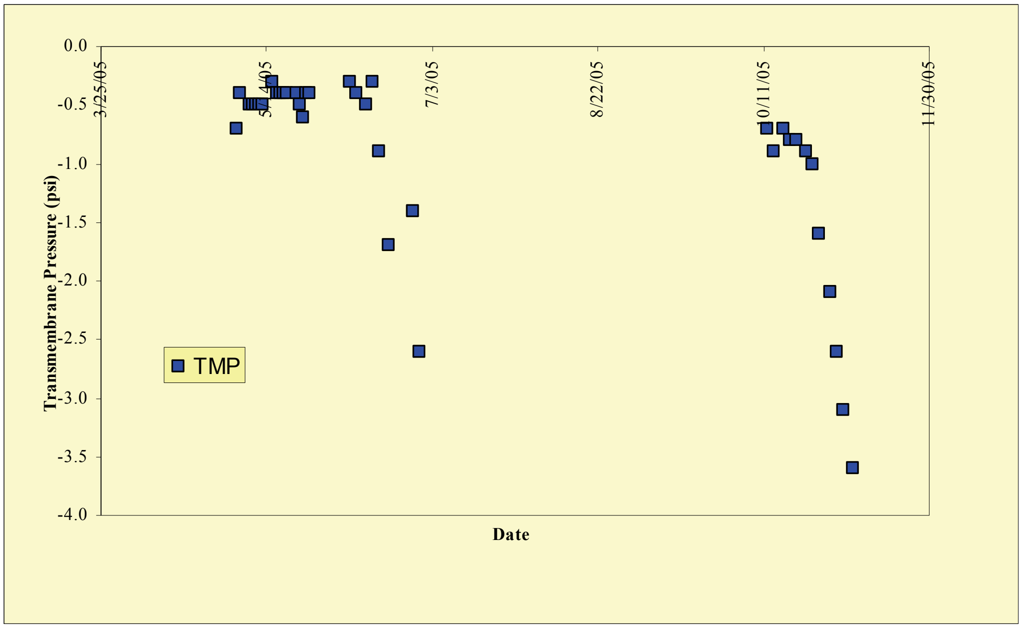

Figure 4.44. TMP during thickening/digestion study using Enviroquip PAD-K system.

4.3 MBR APPLICATIONS AND FACILITY PLANS FOR OAHU

A comprehensive study of potential applications for MBRs on Oahu including satellite reclamation, plant expansions, plant upgrades to facilitate recycling, and decentralized treatment for proposed and new developments has been completed. The "Honolulu MBR Feasibility Study" is a stand-alone document included in this report as Appendix I.

CHAPTER 5

RESULTS AND DISCUSSION: SELECTION OF MBR EQUIPMENT

5.1 BACKGROUND

Many engineers, owners, operators, and vendors who have heard of the Honolulu MBR Pilot Study have asked: Which MBR is the best? In lieu of a more direct answer, attempts have been made to evaluate and highlight the differences between the MBRs, including both cost and noncost factors. This study has found that all of the MBR technologies are capable of producing extremely high-quality effluent and are viable and reliable technologies for wastewater treatment. However, certain site-specific design requirements on any given project for which MBRs are considered can assist in the selection of the most appropriate MBR. A variety of information has been gathered to assist the industry with selection criteria.

5.2 MBR CONFIGURATIONS

Each of the six MBRs included in this study is different in both physical configuration and operating mode. Some of the MBRs are very simply configured, and some are much more complex. This disparity leads to differences in operation and maintenance requirements including pretreatment needs (screen size and equalization), power usage, chemical usage, ease of operation, control complexity, cleaning frequency, cleaning modes and complexity, and equipment durability. Table 5.1 gives the basic physical characteristics of the different MBR configurations. Table 5.1 indicates that both microfiltration and ultrafiltration membranes are utilized, that the membranes are located either in the aeration basin or in a separate membrane compartment, and that both hollow-fiber and flat-sheet membranes are utilized. In addition, the hollow-fiber types are all different; some are supported by an internal backing and others are unsupported. Reduced resistance to flow due to flat-sheet configuration and relatively large pore size makes it feasible to operate the Enviroquip units under gravity pressure. All of the other configurations must be operated with permeate pumps; however, the pressure drop across the membranes (TMP) is very low (−1 to −4 psi). Apparently, approximately 50% of the Enviroquip units currently existing and or being designed are configured to operate in gravity mode with the remainder operated in pumped mode. The Huber unit is perhaps the most unique since the membranes are mounted on a shaft that slowly rotates. This structure allows the scour air to be located on only one side since the membranes can be rotated through the air.

Table 5.1. General characteristics of six pilot MBR systems

Vendor	Membrane configuration	Membrane location	Membrane type	Pore size (μm)
Enviroquip (Kubota)	Vertical flat panel	Aeration basin	Microfiltration	0.4
Huber	Rotating flat panel	Aeration basin	Ultrafiltration	0.02
Ionics (Mitsubishi)	Horizontal hollow fiber (Steripore)	Aeration basin	Microfiltration	0.4
Koch	Vertical hollow fiber	Cell compartment	Microfiltration	0.1
US Filter (Memtec)	Vertical hollow fiber	Cell compartment	Microfiltration	0.08
Zenon	Vertical hollow fiber (ZeeWeed 550d)	Cell compartment	Ultrafiltration	0.04

5.3 MBR OPERATING AND CLEANING MODES

Table 5.2 gives the operating modes of the different MBR configurations. All of the membranes are operated in an outside-to-inside flow mode under negative pressure. Table 5.2 indicates that all the MBRs include coarse bubble air scour to prevent sludge from caking on the membrane surface. Only Zenon incorporates a discontinuous air scour in which the air cycles on and off 50% of the time. Coarse bubble aeration is necessary in order to form large bubbles that are effective at shearing the sludge cake from the membrane surface. All of the MBRs except Huber utilize a permeation relaxation mode. In the relaxation mode, the permeate pump is periodically turned off while the air scour remains on to release suction on the sludge cake from the membrane and facilitate enhanced scouring action. The typical relaxation frequency is 1 min out of every 10 min, but this frequency is adjustable usually between 1 and 3 min out of 10 min. Existing Huber MBRs (including the pilot unit in this study) incorporate an intermittent water scour system in which mixed liquor is pumped through nozzles through which the membranes rotate. The water scour feature has been eliminated from new Huber MBR units. Two of the hollow-fiber MBRs (US Filter and Zenon) incorporate intermittent backpulsing with permeate to clean the membranes. However, this feature has been phased out of new MBR units. In both cases, the new MBR systems will have backwash capability to be used during start-up and for periodic cleaning but will not be used all the time.

Table 5.2. Pilot MBR operating modes

Vendor	Operating mode
Enviroquip (Kubota)	Continuous air scour and permeation relax
Huber	Continuous air scour on one side and intermittent water scour[a]
Ionics (Mitsubishi)	Continuous air scour and permeation relax
Koch	Cyclic air scour (33% time on) and intermittent backpulse (10 s/5 min)
US Filter (Memtec)	Continuous air scour, permeation relax, and intermittent backpulse (30 s/12 min)[a]
Zenon	Cyclic air scour (50% time on), permeation relax, and intermittent backpulse (15 s/15 min)[a]

[a]These features provided on existing units but phased out of new designs.

Two types of cleaning are incorporated into MBR operations: maintenance cleaning (Table 5.3) and recovery cleaning (Table 5.4). Maintenance cleaning is the more-or-less continuous cleaning that is required to maintain membrane flux at low TMP. The critical flux is generally considered to be that flux at which the MBR can be continuously operated without an increase in TMP. When fouling occurs such that the TMP increases for a constant flux, recovery cleaning is required. This fouling may or may not be permanent as indicated by determining the clean water permeability over time. Recovery cleaning is more vigorous cleaning required to recover flux rates at reasonable TMPs. In this pilot test, we utilized chlorine (1000 to 2000 ppm) and hydrochloric acid (1%) recovery cleaning operations and found them both to be easy to conduct and highly effective.

Table 5.3 indicates that most of the vendors utilize permeate relaxation as their main form of maintenance cleaning. In this mode, the suction holding the sludge cake layer on the membrane surface during permeation is released by disengaging the permeate pump to allow enhanced sloughing. Only Huber does not require this cleaning mode, allowing it to employ at least 10% less membrane area to permeate the same amount of water as the other vendors. The relaxation interval is generally 1 min out of 10 min but is adjustable to 2 or 3 min out of 10. Koch, US Filter, and Zenon incorporate backpulsing with permeate for maintenance cleaning either on a regular basis or as needed. This requirement will lead to slightly increased overall chemical usage. Backpulsing generally necessitates additional tankage (permeate surge tank, chlorine tank, and feed pump), piping, and valving, which tends to complicate the overall system unless reversible permeate pumps are utilized.

Table 5.3. Maintenance cleaning requirements

Vendor	Maintenance cleaning type	Maintenance cleaning interval
Enviroquip (Kubota)	Relaxation	1, 2, or 3 min per 10 min
Huber	None	None
Ionics (Mitsubishi)	Relaxation	1, 2, or 3 min per 10 min
Koch	Permeate backpulse	5 to 15 min
US Filter (Memtec)	Relaxation and chlorine backpulse	1, 2, or 3 min per 10 min, weekly
Zenon	Relaxation and chlorine backpulse	1, 2, or 3 min per 10 min, as needed

Table 5.4 indicates that Enviroquip, Huber, Ionics, and Koch utilize an in situ recovery cleaning in which the chlorine solution is simply pumped inside the membranes from the permeate side and left to sit for 2 h after which the system is restarted. This process utilizes much fewer chemicals and is simpler than the full chemical soak specified by US Filter and Zenon. There are also differences in the recommended interval with Ionics and US Filter recommending twice as many recovery cleanings per year as Enviroquip, Zenon, and Huber.

Table 5.4. Recovery cleaning requirements

Vendor	Recovery cleaning type	Recovery cleaning interval
Enviroquip (Kubota)	Chlorine backwash in situ	Biannual
Huber	Chlorine backwash in situ	As needed
Ionics (Mitsubishi)	Chlorine backwash in situ	Quarterly
Koch	Chlorine backwash in situ	As needed
US Filter (Memtec)	Chlorine soak in drained cell	Quarterly
Zenon	Chlorine soak in drained cell	Biannual

5.4 MBR DESIGN PARAMETERS

There are also differences in design parameters between the different MBRs that can result in different total membrane costs, as well as differences in operation and maintenance. Table 5.5 shows several important design parameters. The importance of these parameters is discussed below.

Table 5.5. Design criteria for six different pilot MBRs

Vendor	Design flux (GFD)	Peak flux (GFD)	TMP (−psi)	Air use (CFM/100 ft^2)	Screen pore size (mm)
Enviroquip (Kubota)	14.7	43	0.1–4	3.0 1.8 for >4 MGD	3
Huber	13–14	33.5	2–6	1.4–1.8	3
Ionics (Mitsubishi)	10	32.3	1–4	1.8	1–2
Koch	14.3	26.8	0.2–2	1.0	3
US Filter (Memtec)	15	30	1–4	1.6	2
Zenon	10–15	22	2–8	1.7–1.8	1–2

5.5 MBR SELECTION CONSIDERATIONS

So how does an owner or engineer go about selecting an MBR? First of all, a preselection process that incorporates life cycle costs and noncost factors should be used to select the membrane vendor before the initiation of design work in order to provide the most cost-effective design. In general, one should consider water quality, site-specific requirements, costs, and differences in operation and maintenance requirements. Because the water quality of the permeate produced by each of the five MBRs has been outstanding and water quality differences among the units are essentially negligible, other factors such as operation and maintenance become very important for determining which MBRs are the most desirable. It has been pointed out above that there are differences between the different MBRs. These differences can be divided into cost issues and noncost issues. Specifically, there are differences among them in membrane type and configuration as well as in the minimum membrane area required for a given design. There are also differences in power and chemical usage and pretreatment needs, and there may be differences in equipment durability. These are all cost issues. The principal noncost issues include ease of operation; control complexity; cleaning frequency, modes, and complexity; and company profiles and experience. In some cases, site-specific needs may be important such as operator availability or lack thereof, a need for simplicity, high electricity costs, screening requirements, and peak flow factors.

Table 5.6 shows a subjective assessment of the complexity factor for these five MBR units. Table 5.7 shows several other factors for which differences can be observed. Table 5.8 shows how the ratio of peak flow to average design flow affects the total membrane area required for each type of MBR.

Table 5.6. Assessment of MBR complexity

Vendor	Level of complexity		
	Simplest	Medium	Most complex
Enviroquip (Kubota)	Just a blower and a permeate pump		
Huber		Add a more complex rotating shaft	
Ionics (Mitsubishi)	Just a blower and a permeate pump		
Koch			Add cycling pneumatic valves and cycling backflush system
US Filter (Memtec)			Add cycling backflush system
Zenon			Add cycling pneumatic valves and cycling backflush system

Table 5.7. Assessment of several factors

Vendor	Factor			
	Screenings	Electricity costs	Cleaning frequency	Chemical usage
Enviroquip (Kubota)	Less Use 3 mm	Highest on small systems (<4 MGD)	Least	Least
Huber	Less Use 3 mm	Medium	Least	Least
Ionics (Mitsubishi)	More Should use 1 mm	Medium	Less	Less
Koch	Less Use 3 mm	Medium	Less	More
US Filter (Memtec)	More Should use 1 mm	Lowest	Most	More
Zenon	More Should use 1 mm	Medium	Less	More

Table 5.8. Effects of design flux on MBR selection

Vendor	Effect of: Peak factor up to 2.0	Peak factor of 2.5	Peak factor of 3.0
Enviroquip (Kubota)	Fewer membranes	Fewer membranes	Smallest
Huber	Larger	Less membrane	Larger
Ionics (Mitsubishi)	Most membranes	Larger	Larger
Koch	Fewer membranes	Larger	Larger
US Filter (Memtec)	Fewer membranes	Larger	Larger
Zenon	Larger	Most membranes	Most membranes

In addition, site-specific requirements related to operation and maintenance can be employed to help select the most appropriate MBR for each application. One consideration is the availability of qualified operators. MBR systems may require fewer operators; however, these operators have to be well trained and quite skilled in order to understand the relatively complex MBR systems and be able to diagnose problems and make corrections relatively rapidly. Another consideration is the simplicity or degree of complexity of the MBR in terms of operating mode and degree of maintenance needed. For some applications, a simpler system requiring less frequent and simpler-to-perform maintenance may be desirable, as in situations where operations staff may not always be on site (remote facilities or decentralized sewer mining operations). Another consideration is electrical costs. Since electrical costs are the largest portion of the maintenance cost for MBRs, at some project locations where electricity rates are high, the amount of power usage could influence the selection of an MBR. Another consideration is the prescreening requirements, since some MBRs require finer prescreens than others, thus generating more screenings for processing, storage, or disposal. In some locations, it might be desirable to limit screening production and handling. A final site-specific consideration is related to the design flux of the MBRs. The MBRs all have different design fluxes and different peak flow capabilities (Table 5.5). The ratio of peak flux to design flux will determine which MBR system will require the least total membrane area. These site-specific factors that are mostly noncost considerations can help the design engineer to select the most appropriate MBR for a given situation.

5.6 RECOMMENDATIONS

It is apparent that all six MBR technologies produce excellent permeate suitable for water recycling. It is also apparent that there are many factors other than just water quality that are important in the selection of an MBR system and that there are differences between MBRs with respect to these factors. These include both cost and noncost factors. MBRs constitute excellent technology producing exceptional effluent water that is easily converted into recycled water, but these systems do require operations staff and are not maintenance free. The owner or engineer should be rational in his choice of vendor. It does not appear to be necessary to choose the most experienced North American vendor since the other vendors have experience in other areas such as Asia and/or Europe and since all are backed by reputable companies. It is apparent that the most important factors are the 20-year life cycle costs (which consider capital costs, operation and maintenance costs, and membrane warranty) and noncost factors for which a site-specific evaluation is required. It is further recommended that conservatism be incorporated in terms of design flux (lower fluxes will allow membranes to last longer), the use of smaller fine screens, and incorporation of redundancy for all critical equipment.

CHAPTER 6

RESULTS AND DISCUSSION: MBR MEMBRANE FOULING

6.1 OPERATING CONDITIONS

The goals of the bench-scale studies include (i) to investigate and compare the bacterial diversity in MBR biofilms and in MBR bulk liquor in relation to membrane-fouling rates and water quality parameters such as EPS and SMP; and (ii) to investigate and determine relationships among critical flux SRT, EPS, SMP, particle size distribution (PSD), viscosity, time to filter, colloidal TOC, and other parameters. These are basic research needs for MBR systems. Bench-scale studies are to be conducted to allow closer attention to operations and to facilitate modification and destructive analysis techniques such as biofilm analysis with scanning electron microscopy. Bench-scale Enviroquip and Ionics MBR systems were constructed (see Figure 3.9 above). They were initially operated in the Environmental Engineering Lab at UH (December 5, 2005, to January 6, 2006). Due to difficulties in obtaining and maintaining fresh wastewater at the lab, the bench members were moved to Honouliuli and reseeded on January 16, 2006. Basic operating and water quality data are presented below.

6.2 EVALUATION AND MONITORING OF MBR BIOFOULING

6.2.1 Process Operating Data

The bench-scale reactors (one flat-plate type and one hollow-fiber type) were operated via programmable logic controllers for feed, mixed-liquor recycling, anoxic mixing, and permeation. A SCADA system was utilized for monitoring of permeate flow rate and TMP. pH controllers were employed to maintain the pH at nearly 7.0. The bench MBRs were operated at a constant nominal flux of 10 GFD. The recycling ratio was approximately 8:1 in both MBRs. The HRT was approximately 24 and 28 h in the Ionics and Enviroquip MBRs, respectively. The SRT was 20 days. Figures 6.1, 6.2, and 6.3 show TMP, MLSS, and DO data, respectively. The TMP values are all well below that which would necessitate recovery cleaning (−3 psi). The initial MLSS values are large because the bench units are seeded with about 75% Koch mixed liquor.

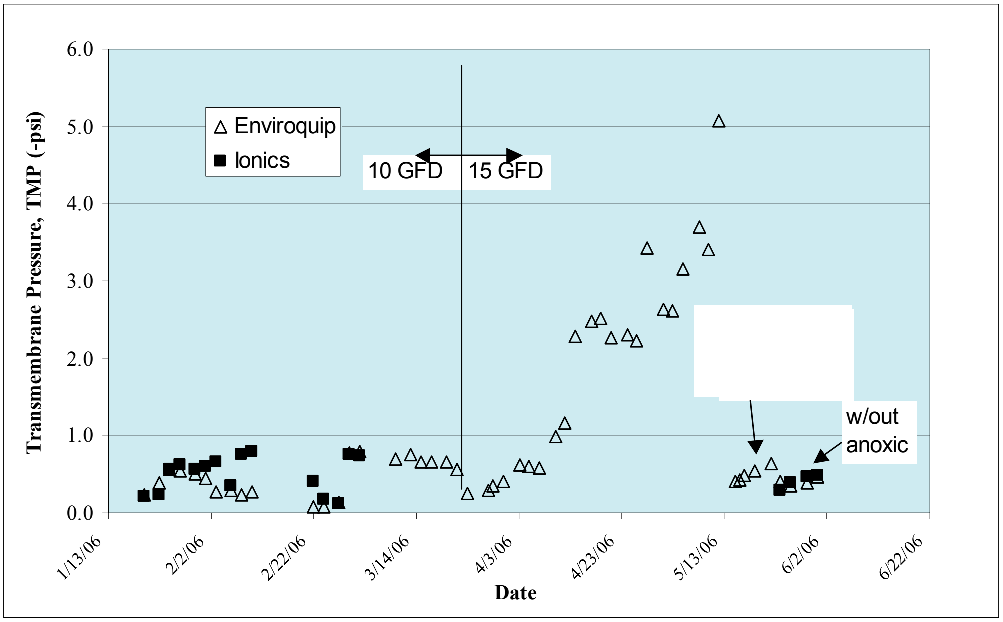

Figure 6.1. TMP in bench-scale MBRs (raw wastewater).

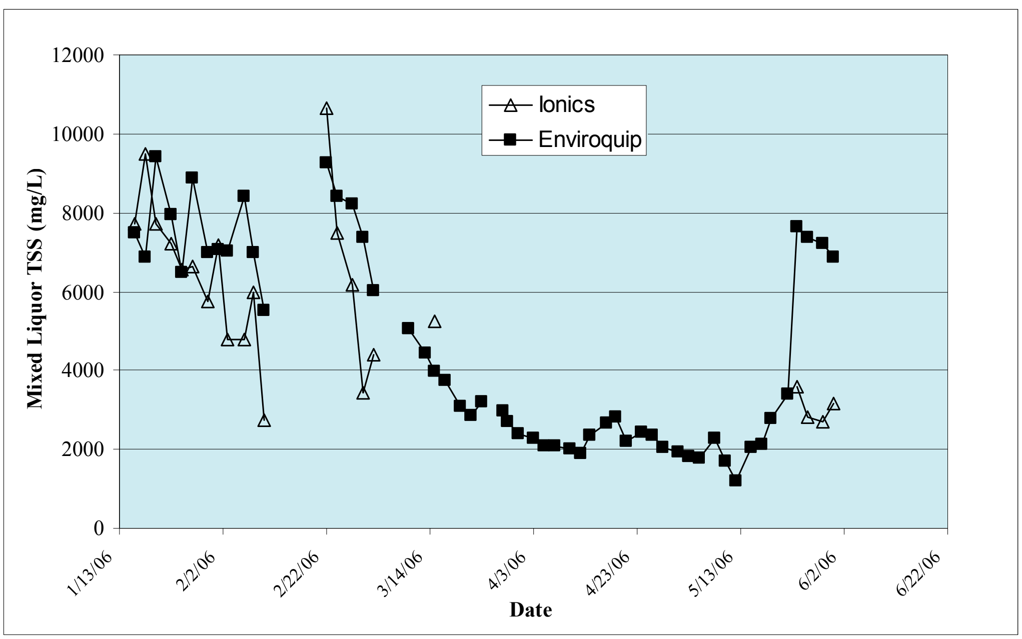

Figure 6.2. MLSSs in bench-scale MBRs (raw wastewater).

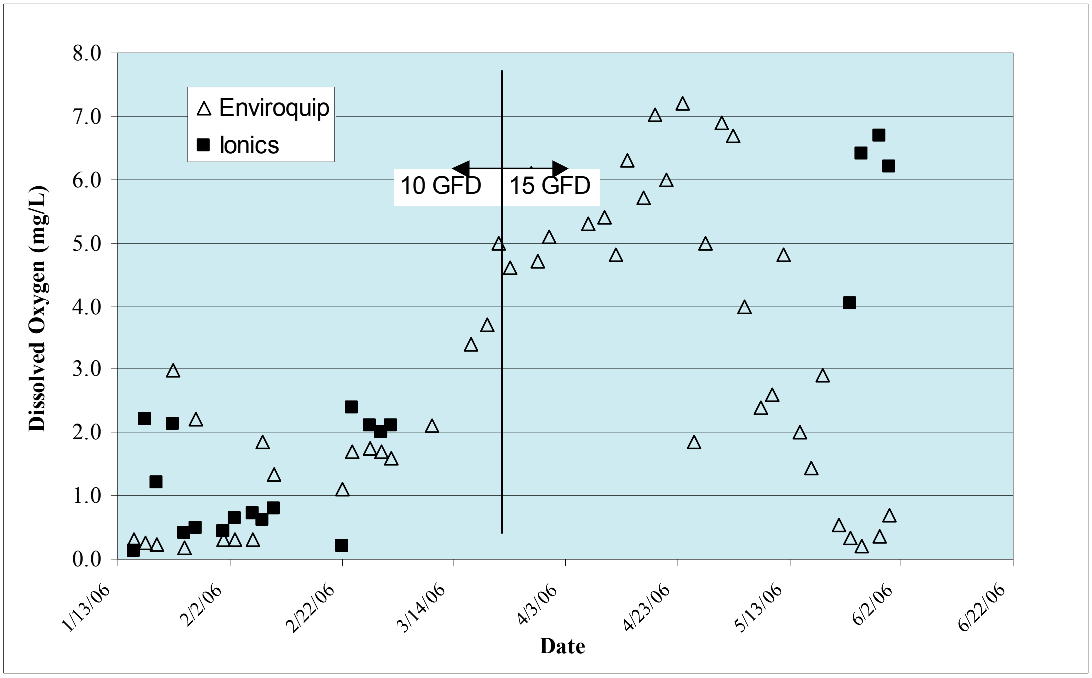

Figure 6.3. TMP in bench-scale MBRs (raw wastewater).

6.2.2 Water Quality Data

Water quality data are presented in Figures 6.4 through 6.7 and Table 6.1. Overall, the bench-scale MBRs performed like the pilot-scale MBRs and produced excellent effluent (permeate) water quality. Minor differences included less denitrification in the Ionics MBR than in the Enviroquip unit due to problems with the recirculation pump.

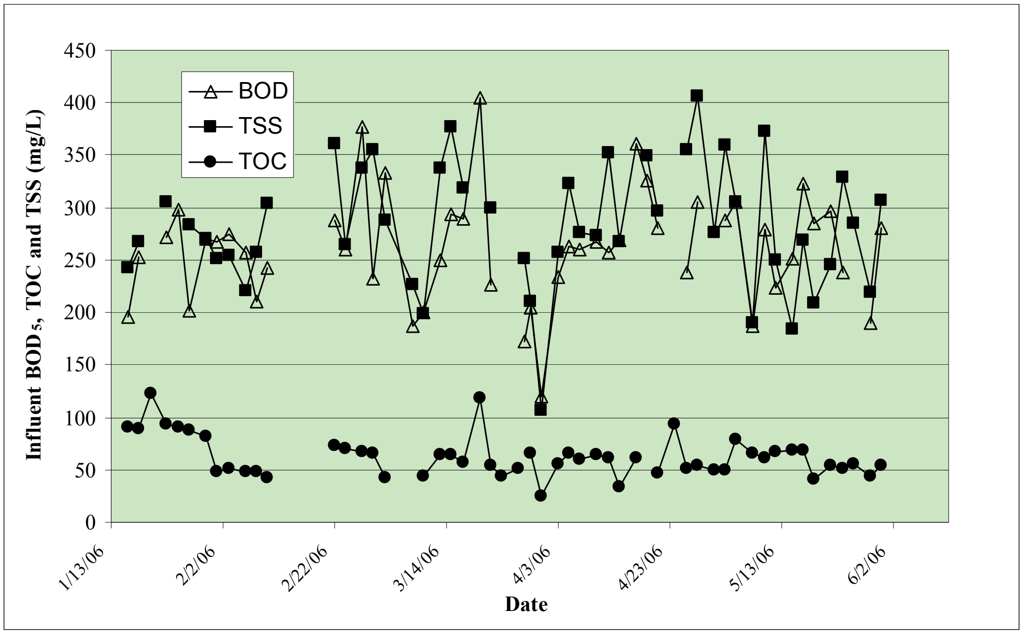

Figure 6.4. Influent BOD, TOC, and TSS for bench-scale MBRs (raw wastewater).

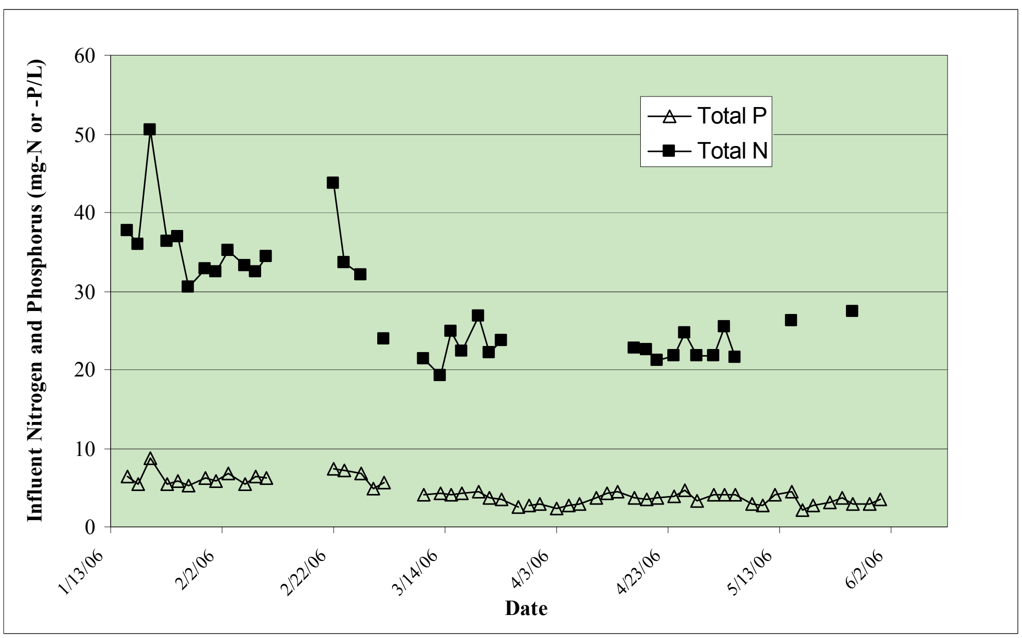

Figure 6.5. Influent nitrogen and phosphorus for bench-scale MBRs (raw wastewater).

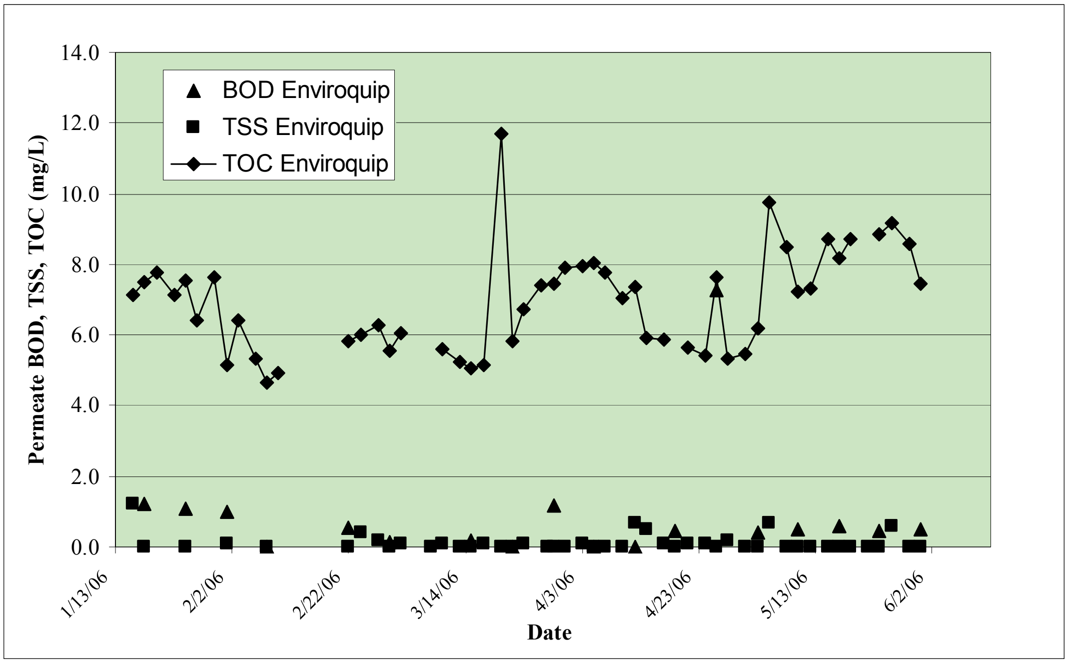

Figure 6.6. Effluent (permeate) BOD, TOC, and TSS for bench-scale Enviroquip MBR.

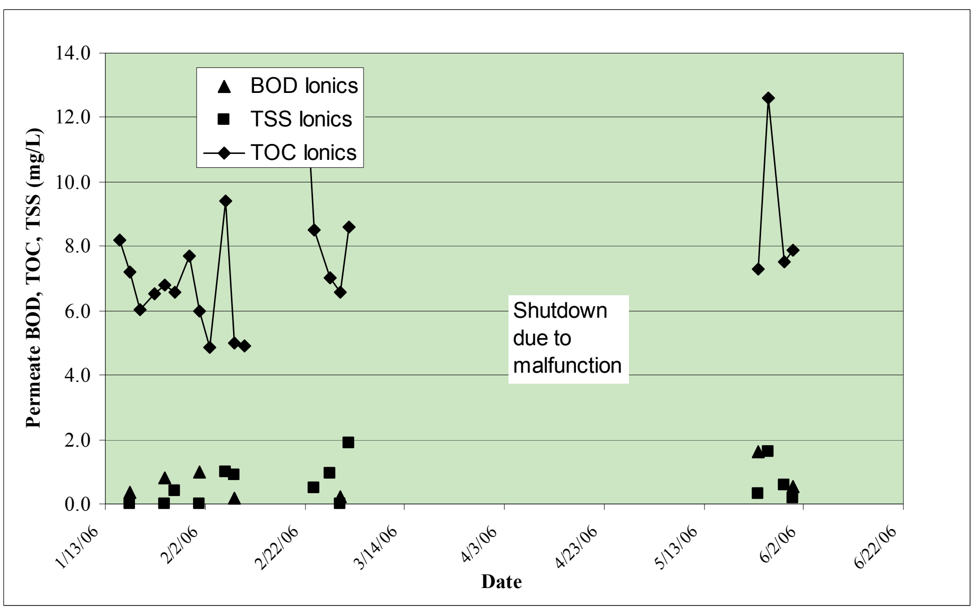

Figure 6.7. Effluent (permeate) BOD, TOC, and TSS for bench-scale Ionics MBR.

Table 6.1. Average water quality data and removal efficiencies (in parentheses) for the bench-scale MBRs (raw wastewater)

Analyte	Value for: Influent	Enviroquip permeate	Ionics permeate
BOD_5 (mg/L)	261	0.9 (99.7%)	0.7 (99.7%)
TSS (mg/L)	282	0.12 (99.9%)	0.60 (99.8%)
TOC (mg/L)	63	6.9 (88.9%)	7.5 (88.1%)
COD (mg/L)	519	13 (97.5%)	16 (97.3%)
O&G (mg/L)	23.8	0.0 (100%)	0.0 (100%)
Nitrogen, total (mg of N/L)	28.8	16.5 (42.7%)	24.4 (17.1%)
Ammonia (mg of N/L)	18.8	1.3	1.2
Nitrate (mg of N/L)	NA	15.2	22.9
Color (Pt-Co)	163	27 (83.7%)	27 (83.3%)
UVT_{254} (%)	48	76	73
Turbidity (NTU)	NA	0.30	0.50
pH	7.6	7.5	7.1
TDS (mg/L)	686	678	680
Alkalinity (mg of $CaCO_3$/L)	81	57	20

6.2.3 SMP and EPS

The concentrations of SMP and EPS have been monitored in the influent, mixed liquors, and permeates for the bench MBRs. Figures 6.8 through 6.15 show the carbohydrate and protein fraction data collected. Figure 6.8 shows that carbohydrate SMP concentrations are smaller than are EPS concentrations. In addition, the two different bench-scale MBRs have very similar SMP concentrations. Generally, it appears that the flat-plate Enviroquip MBR sludge has somewhat higher EPS than does the hollow-fiber Ionics MBR sludge. This finding could be attributable to the somewhat different hydraulic regimen experienced by the sludge. This theory will be investigated further. Figure 6.9 shows protein fractions of SMP and EPS with trends similar to those depicted in Figure 6.8.

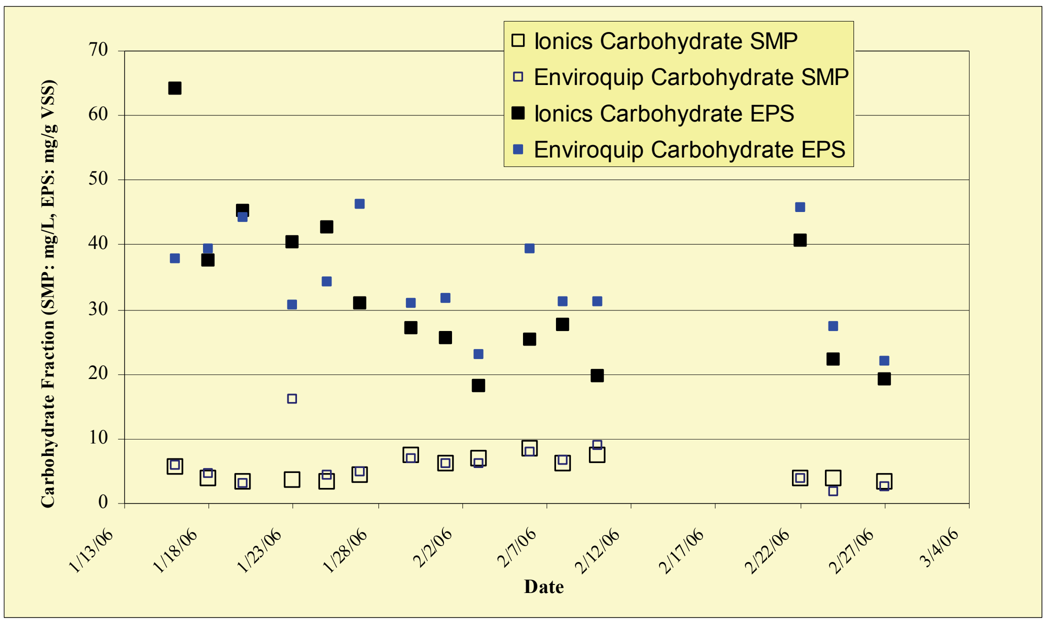

Figure 6.8. Carbohydrate fractions of SMP and EPS in bench-scale MBRs.

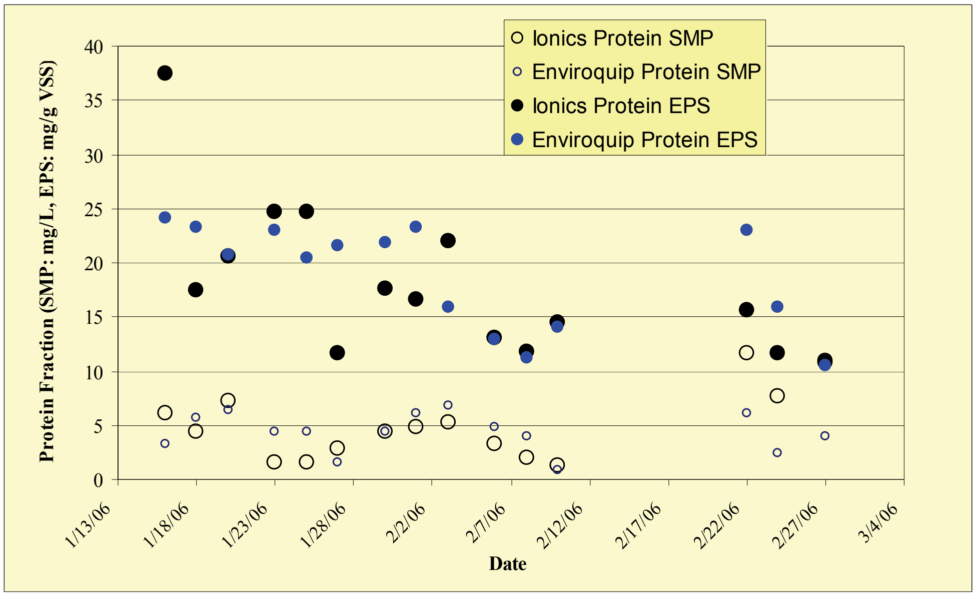

Figure 6.9. Protein fractions of SMP and EPS in bench-scale MBRs.

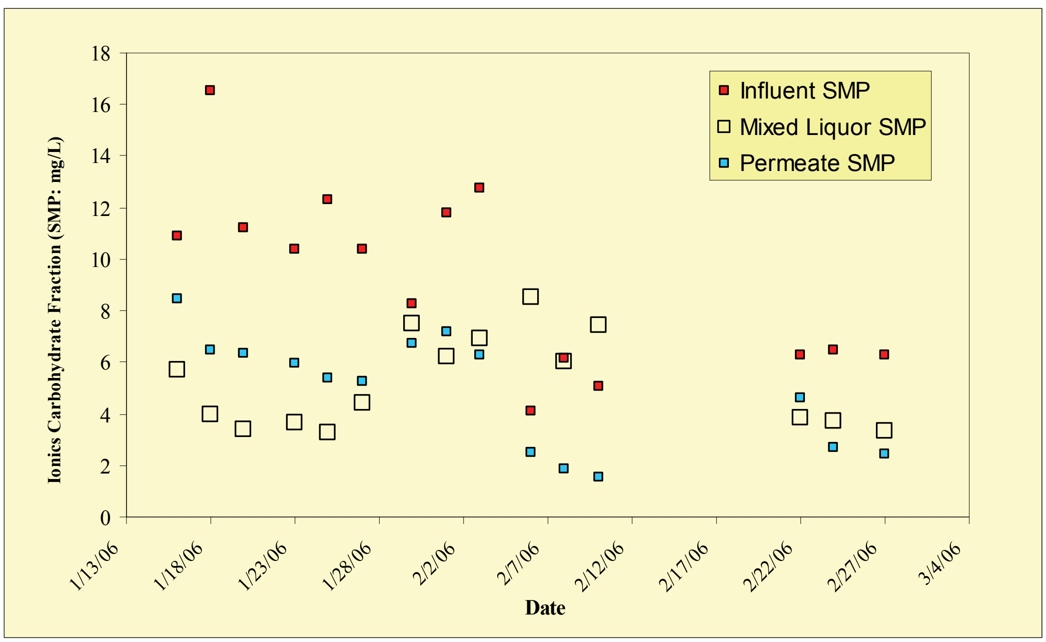

Figure 6.10. Carbohydrate SMP for Ionics bench-scale MBR.

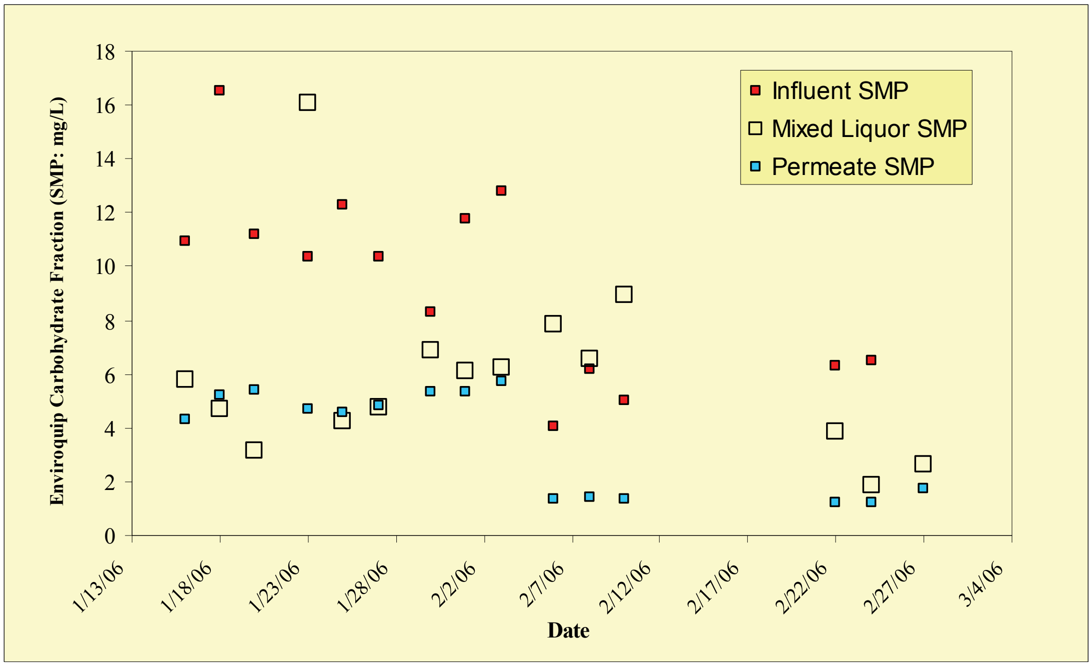

Figure 6.11. Carbohydrate SMP for Enviroquip bench-scale MBR.

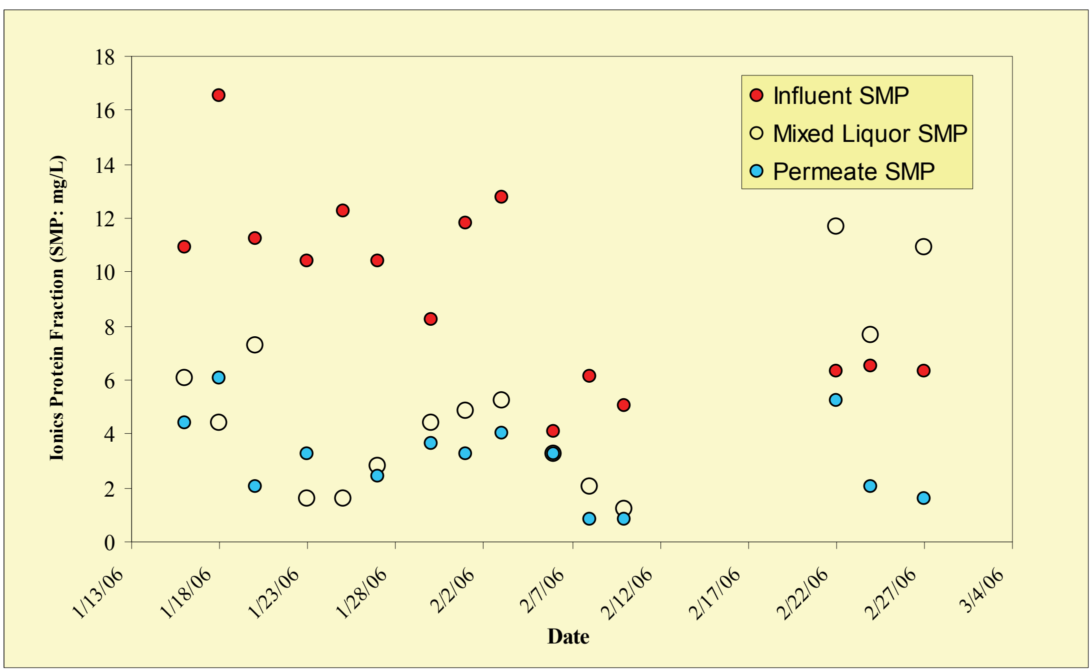

Figure 6.12. Protein SMP for Ionics bench-scale MBR.

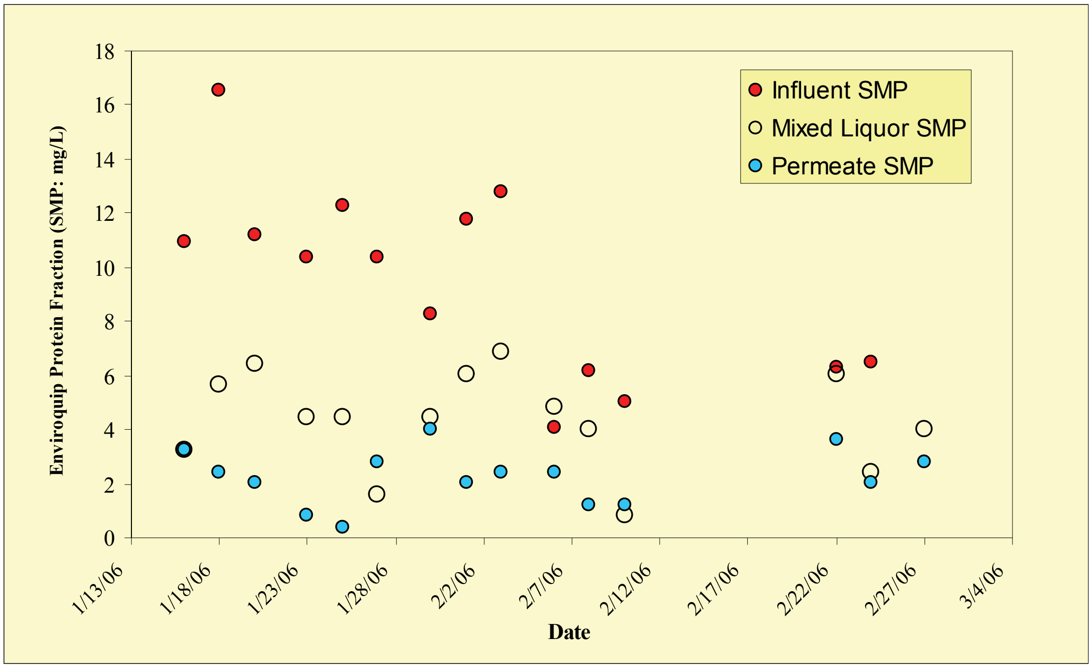

Figure 6.13. Protein SMP for Enviroquip bench-scale MBR.

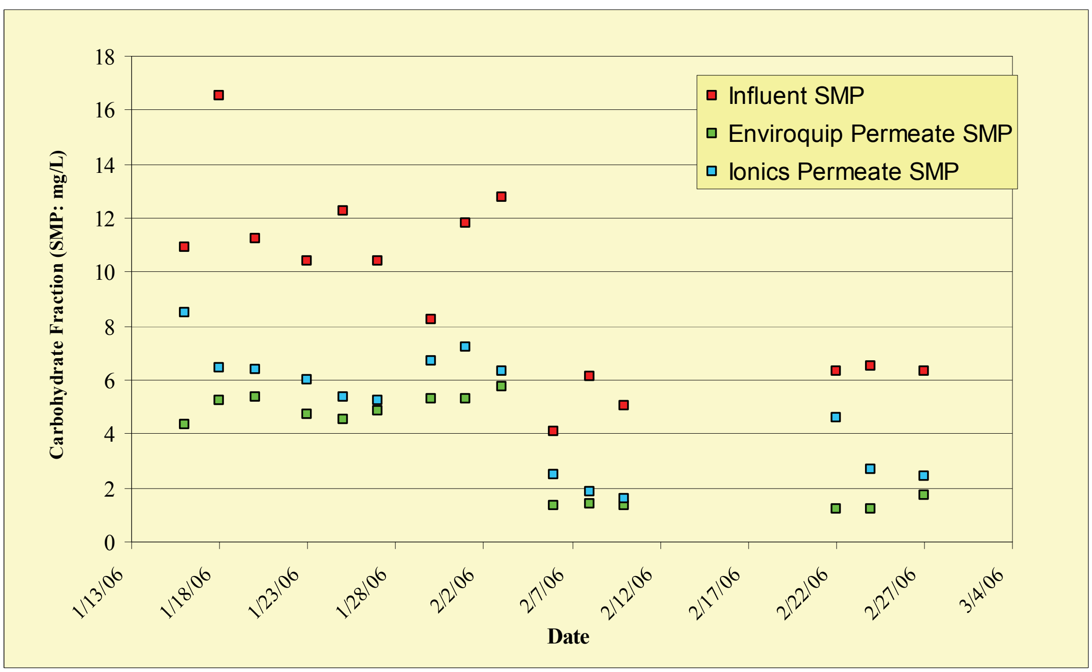

Figure 6.14. Comparison of permeate carbohydrate SMP levels from bench-scale MBRs.

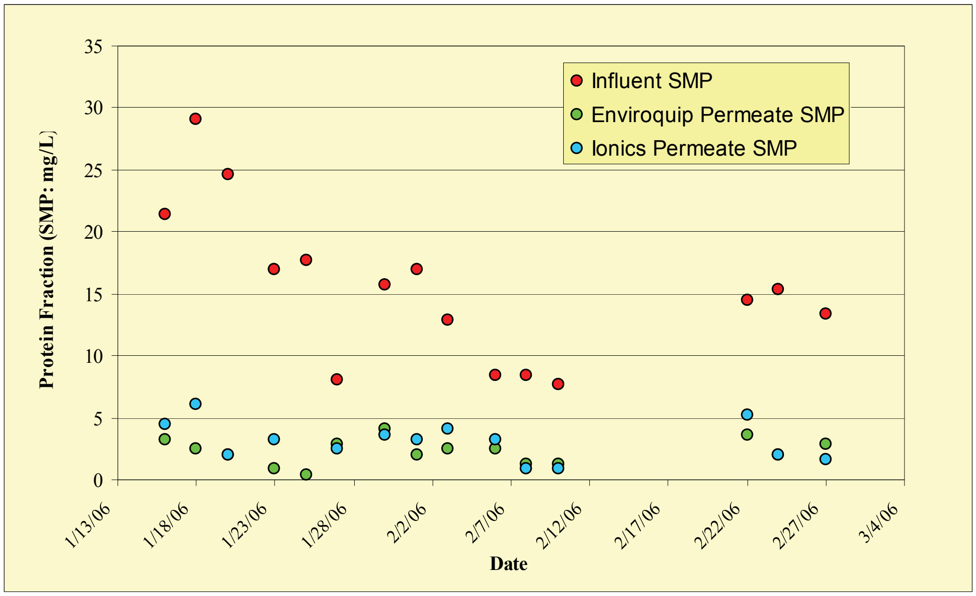

Figure 6.15. Comparison of permeate protein SMP levels from bench-scale MBRs.

Table 6.2. Average SMP and EPS concentrations for bench-scale MBRs and SMP removal rates across the membranes (in parentheses)

	Value for:				
Analyte	**Influent**	**Enviroquip permeate**	**Ionics permeate**	**Enviroquip liquor**	**Ionics liquor**
Carbohydrate SMP (mg/L)	9.5	3.5 (40%)	4.8 (5%)	5.7	5.1
Protein SMP (mg/L)	10.7	2.4 (36%)	2.6 (39%)	3.7	4.5
Carbohydrate EPS (mg/gVSS)	NA	NA	NA	33.7	30.9
Protein EPS (mg/gVSS)	NA	NA	NA	16.7	16.8

Note: gVSS = grams of volatile suspended solids

6.2.4 Membrane Resistances and Critical Fluxes

Critical flux can be defined as the flux at which there is a rapid and/or irreversible increase in TMP during a normal permeation cycle. The MBR industry is currently debating the term "critical flux" and its utility. There is the concept that MBRs must be operated at nominal fluxes below the critical flux (subcritical) in order for long-term stable operation to be feasible. In other words, minimal membrane cleaning will be required and TMP will remain "low" for a given stable "subcritical" permeate flux. Taking this concept further, it would seem that MBR configurations that afford or allow higher critical fluxes will require less membrane surface area to treat a given design flow rate and would be more cost effective. However, there are at least two confounding issues related to critical flux. The first issue is that the critical flux is not a constant-value parameter for a given MBR. Instead, it is a slave to operating history or more specifically to degree of fouling. And, as such, the critical flux may be a valuable parameter for monitoring certain types of membrane fouling, possibly including long-term fouling, as well as sludge filterability characteristics. The second issue has to do with operating strategies. For example, it is not clear whether under a given set of circumstances, it would be more cost effective to operate at higher fluxes (near or at the critical flux) with reduced membrane areas and concurrent frequent cleanings (necessitating the provision of reliable and effective automated cleaning equipment such as backwashing tanks, valves, etc. and requisite chemical supplies) or to operate at lower fluxes (with additional membrane area) and simpler (possibly not even automated) cleaning systems that are used only infrequently (semiannually or less). The second issue is more of a life cycle cost analysis issue. Both issues do not invalidate the critical flux concept but rather point to its potential importance and the value in studying it. Critical flux is determined by operating an MBR at series of flux rates starting at a lower rate than normal followed by step increases. At each step flux rate, the membranes are operated in their normal relaxation cycle (often with permeation mode for 9 min and relaxed mode for 1 min), and then the flux is stepped up to the next value. The step-flux sequence is repeated several times until a flux is reached in which the TMP response is nonlinear. Often the critical flux is reported as the average of the first nonlinear flux value and the next lower value. As mentioned, the critical flux value is a function of membrane operating history, membrane fouling, and various sludge characteristics. Monitoring the critical flux periodically could be useful for determining fouling rates. The values for critical fluxes are estimated to be 23 and 29 GFD for the Enviroquip and Ionics MBRs, respectively, and reflect the averaging of precritical and postcritical values (see Figures 6.6 and 6.17). These values were determined on March 7 prior to the start of the 15-GFD run for Enviroquip. Attempts to determine the critical flux for the Enviroquip unit on May 12 (at the end of the 15-GFD run) indicated that the critical flux had been reduced to 15 GFD, which was the value of the operating flux. This finding indicates that the membranes were highly fouled, which was also indicated by the very high TMP (>5 psi). During the next runs, critical flux will be determined more frequently such that it may be correlated with other measures of fouling, sludge characteristics, and membrane operating history.

The flux equation for membrane filtration is $J = TMP/\mu R$, where μ is viscosity and R is the resistance to flow. The R has at least three components, including the membrane resistance (R_m), the foulant resistance (R_f), and the cake resistance (R_c). It may be possible to also distinguish a biofilm resistance (R_b). Four sets of measurements can be conducted in order to determine each of the component resistances. The total resistance ($R_T = R_m + R_c + R_f + R_b$) is determined first under process conditions by measuring the TMP_0 at a given flux. The mixed liquor is then removed and replaced with permeate, and the value of $R_m + R_f + R_b$ is determined from TMP_1 (at the same flux). Next, the membranes are vigorously rinsed with pressurized water spray to remove the biofilm and the value of $R_m + R_f$ is determined from TMP_2. Finally, the membranes are chemically cleaned and the value of R_m is determined in tap water from TMP_3. Several researchers have proposed different models to predict the different resistance components; however, none of them is highly satisfying. We are in the early stages of gathering data on the magnitudes of the different resistance components as they relate to biological conditions (e.g., SRT, SMP, and EPS) and environmental conditions (e.g. PSD and viscosity) and working to check agreement with existing models and to develop better models.

Total membrane flux resistance is easily calculated given the operating flux, viscosity, and TMP. Figures 6.18 and 6.19 show the total flux resistance during the various phases of the bench study for the Enviroquip and Ionics MBRs, respectively. The slope of the total resistance line can be considered the fouling rate. For the Enviroquip bench MBR, several observations can be made. First, at 10 GFD, the fouling rate was essentially zero during the period of observation (meaning that the resistance held constant and fouling was minimal). Second, at 15 GFD there appear to be several different fouling rates. The fouling rate starts out low (about 2.8×10^{10} m^{-1} day^{-1}), apparently increases rapidly (about 2.3×10^{11} m^{-1} day^{-1}), slows down for a period (about 2.9×10^{10} m^{-1} day^{-1}), and then again rapidly increases (about 2.3×10^{11} m^{-1} day^{-1}). This phenomenon needs to be investigated further. Third, when supplemental glucose was added to increase the feed strength by 50% for 7 days (with flux held at 15 GFD), the fouling rate did not appear to increase appreciably (about 3.0×10^{10} m^{-1} day^{-1}). Fourth, when the system was modified to eliminate the anoxic zone (with flux held at 15 GFD), the initial fouling rate seemed to decrease (6.4×10^{9} m^{-1} day^{-1}). For the Ionics bench MBR, the fouling rate at 15 GFD (about 4.2×10^{10} m^{-1} day^{-1}) was about three times as rapid as that at 10 GFD (about 1.4×10^{10} m^{-1} day^{-1}). These fouling rates are all at SRT = 20 days.

During the relatively rapid increase in total resistance observed for the Enviroquip bench MBR at 15 GFD, the protein EPS and SMP in the mixed liquor were fairly steady, but the permeate SMP showed an interesting trend (Figure 6.12). This figure shows that the permeate SMP was fairly steady until a certain point (30 to 35 days into the 49-day run) when the value dropped off suddenly (meaning all SMP was retained). This is apparently an indication of severe fouling. No trends in the protein fraction of EPS or mixed liquor SMP that could be useful for predicting fouling were apparent in this data set.

Tests were conducted to estimate the components of the membrane resistance to flux. They were conducted three times for the Enviroquip bench MBR and one time for the Ionics bench MBR. The first test was conducted on March 7 prior to increasing the flux from 10 to 15 GFD and represents an unfouled (or very lightly fouled) condition. The second test was conducted on May 12 at the end of the 15-GFD run (after 49 days) when the membranes were highly fouled. The third test was conducted on May 22 after operation of the MBR with supplemental glucose to increase feed BOD by 50% for 7 days (additional BOD = 165 mg/L). After each test, the membranes were chemically cleaned with bleach. Membrane resistance component values for the first test were reported in the Fifth Progress Report. Those values were adjusted to 15 GFD to facilitate comparisons with the later test data as reported in Table 6.3. The data in Table 6.3 indicate several things, including (i) the membrane resistance, R_m, increased over time, indicating either permanent fouling (loss of permeability) or incomplete cleaning between runs (the later is more likely and will be investigated further); (ii) the foulant resistance increased by more than 100 times after the rate switched from 10 GFD to 15 GFD and operation continued for 49 days. The cake resistance also increased by nearly 100 times during the same period even though the MLSS was fairly constant, indicating changes in the composition of the biomass in the cake layer; and (iii) the cake and foulant resistances following the supplemental feed operation were much lower than those observed in the highly fouled condition yet higher than the lightly fouled condition (this finding agrees with Figure 2.10, which shows the same fouling rate as that without supplemental feed). Table 6.4 shows the same data set with the addition of biofilm resistances. The technique for determining biofilm resistance has not been perfected, and it is not yet clear if these data are accurate; however, it is presented for discussion. The difference between Table 6.3 and 6.4 is that the "biofilm" resistance seemed to be a very large portion of the non-cake resistance when the membrane was highly fouled (May 12, 2006). Physically, what this means is that there was a gel-like layer that was attached to the membrane after the cake was removed by aeration and that this layer was removed only by spraying with a strong stream of water. It is unclear at this point whether this represents a "biofilm" or a biofilm plus a portion of the cake layer. Answering this question depends upon definitions of each and the establishment of arbitrary test techniques to determine the resistance components. This is an area we are still working on since there are no reported values for biofilm resistance in the literature. The membrane resistances will be monitored periodically to determine fouling rates and assist in model development and calibration.

Table 6.3. Calculated resistance component values for bench-scale Enviroquip MBR

Date (mo/day/year)	R_T (m^{-1})	R_m (m^{-1})	R_c (m^{-1})	R_f (m^{-1})
03/07/2006	1.78×10^{11}	1.41×10^{11} (79%)[a]	2.47×10^{10} (67%)[b]	1.23×10^{10} (33%)[b]
05/12/2006	6.38×10^{12}	3.24×10^{11} (5%)[a]	1.72×10^{12} (29%)[b]	4.33×10^{12} (71%)[b]
05/22/2006	6.24×10^{11}	3.22×10^{11} (52%)[a]	7.80×10^{10} (26%)[b]	2.24×10^{11} (74%)[b]

[a]Percentage of total resistance due to membrane.
[b]Percentage of non-membrane-related resistance.

Table 6.4. Biofilm resistance component values for bench-scale Enviroquip MBR

Date (mo/day/year)	R_T (m^{-1})	R_m (m^{-1})	R_c (m^{-1})	R_f (m^{-1})	R_b (m^{-1})
03/07/2006	1.78×10^{11}	1.41×10^{11} (79%)[a]	2.47×10^{10} (67%)[b]	1.23×10^{10} (33%)[b]	0 (0%)[b]
05/12/2006	6.38×10^{12}	3.24×10^{11} (5%)[a]	1.72×10^{12} (29%)[b]	5.29×10^{10} (1%)[b]	4.27×10^{12} (71%)[b]
05/22/2006	6.24×10^{11}	3.22×10^{11} (52%)[a]	7.80×10^{10} (26%)[b]	1.07×10^{11} (35%)[b]	1.17×10^{11} (39%)[b]

[a]Percentage of total resistance due to membrane.
[b]Percentage of non-membrane-related resistance.

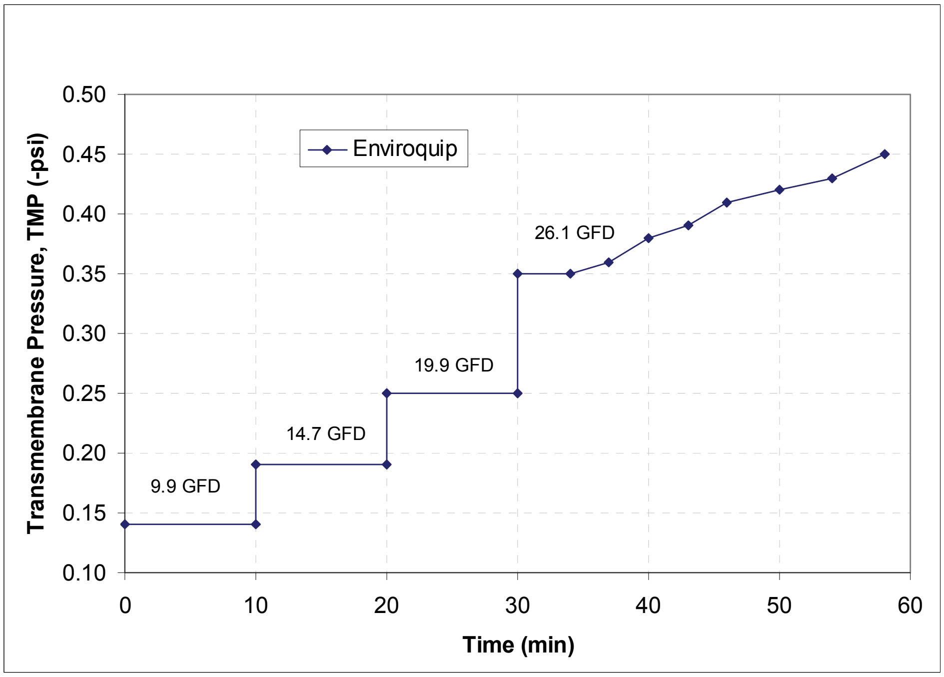

Figure 6.16. Critical flux test data for bench-scale Enviroquip MBR.

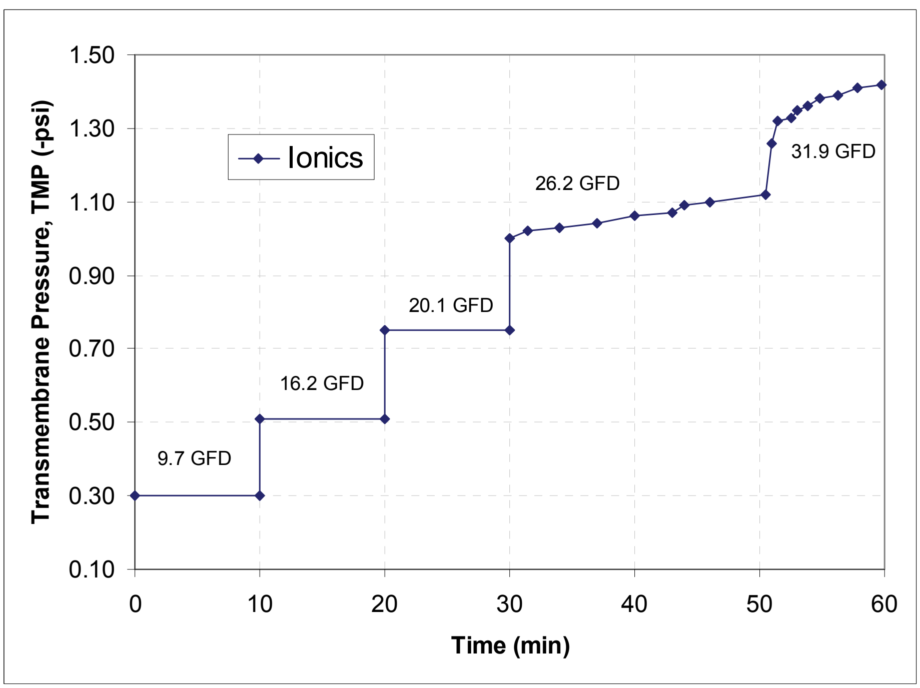

Figure 6.17. Critical flux test data for bench-scale Ionics MBR

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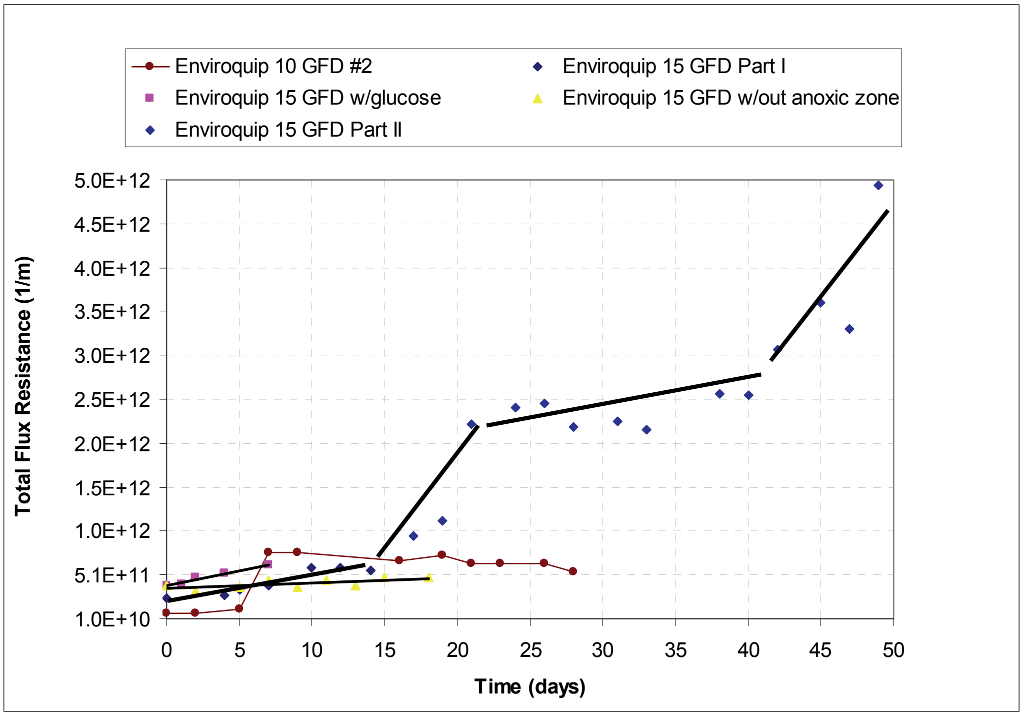

Figure 6.18. Fouling rates during operation of bench-scale Enviroquip MBR.

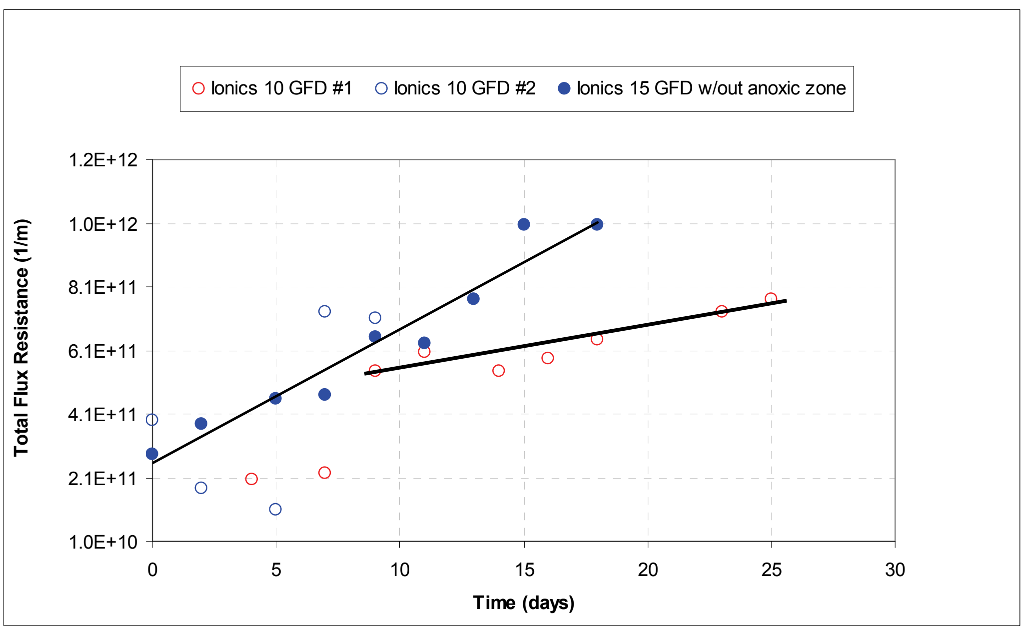

Figure 6.19. Fouling rates during operation of bench-scale Ionics MBR.

CHAPTER 7

RESULTS AND DISCUSSION: DESIGN OF FINE-PORE AERATION SYSTEMS

7.1 BACKGROUND

The goal of the field-scale aeration study is to determine relationships between the α aeration parameter and MLSS, viscosity, SMP, EPS, PSD, SCOD, and TDS. This knowledge is needed for more efficient design of full-scale MBR systems. A pilot aeration column (30-in. diameter, 20-ft height) was constructed at the Honouliuli WWTP (see Figure 3.10 above). An off-gas analyzer was constructed (to measure OTE under steady-state conditions) that included a fuel cell gaseous oxygen analyzer and carbon dioxide–water vapor sorption columns. Three different 8-in.-diameter fine-pore diffusers (ceramic, membrane, and HDPE types) were obtained. Clean water tests were conducted with each diffuser in triplicate at multiple specific air flow rates. Process water tests were conducted at a range of MLSS values ranging from approximately 3 to 18 g/L.

7.2 CORRELATION OF WATER QUALITY AND α VALUES FOR MBRs

Clean water tests have been conducted with each diffuser in triplicate at multiple specific air flow rates. Table 7.1 shows all of the clean water test data collected. Figure 7.1 gives the average overall mass transfer coefficient (K_La_{20}) for the three different diffusers. Figure 7.2 shows the average values of standard OTE determined. These data generally compare well with vendor literature and are used to determine the *α* factor following off-gas testing of mixed liquor.

Table 7.1. Clean water aeration test results

Clean Water Test Results												
Aerator Manufacturer	Test	Diffuser Type	Air Flow Rate	Local temp.	Local barom.	Water temp.	K_La_{20} probe 1[a]	K_La_{20} probe 2[a]	$C^*_{\infty 20}$ probe 1[a]	$C^*_{\infty 20}$ probe 2[a]	SOTE probe 1[a]	SOTE probe 2[a]
			SCFM[b]	° F	in. Hg	° C	1/h	1/h	mg/L	mg/L	%	%
AECOR	1	Membrane	1	79	29.84	25.0	5.043	5.090	10.003	9.835	23.876	23.695
	2	Membrane	1	73	29.92	24.6	5.490	5.860	10.016	10.603	26.025	29.410
	3	Membrane	2	76	29.77	25.0	14.387	13.235	10.269	10.991	34.962	34.427
	4	Membrane	2	71	29.80	24.1	15.991	15.504	9.511	10.381	35.993	38.090
	5	Membrane	3	71	29.91	24.2	27.811	25.670	10.411	10.067	45.682	40.774
	6	Membrane	3	73	29.84	24.4	29.068	26.041	10.075	10.456	46.204	42.961
AECOR	7	Ceramic	1	69	29.91	23.5	15.638	13.891	9.547	11.019	70.665	72.445
	8	Ceramic	1	69	29.91	25.6	12.180	11.253	11.188	11.278	64.496	60.070
	9	Ceramic	1	76	29.90	25.8	8.614	7.893	10.924	10.417	44.540	38.916
	10	Ceramic	1	74	29.91	25.6	7.349	7.173	9.668	10.406	33.628	38.332
	11	Ceramic	1.5	71	29.94	24.5	23.449	20.833	10.324	10.908	76.389	71.707
	12	Ceramic	1.5	71	29.94	25.1	18.956	17.357	10.269	10.703	61.423	58.621
	13	Ceramic	2	74	29.96	24.2	18.230	16.893	10.137	10.853	43.733	43.390
	14	Ceramic	2	74	29.96	24.4	18.777	15.392	8.540	10.934	37.947	39.829
Lakeside	15	HDPE[c]	1.5	77	29.92	25.6	15.172	13.422	10.331	10.904	49.459	46.180
	16	HDPE[c]	1.5	74	29.91	24.6	16.001	14.357	10.152	10.759	49.300	46.881
	17	HDPE[c]	3	72	29.77	24.0	24.173	22.305	10.054	10.669	38.343	37.547
	18	HDPE[c]	3	69	29.77	24.2	28.269	26.866	10.345	10.606	46.141	44.957
Clean Water Summary												
Diffuser Type		Q_{air}	Avg. $C^*_{\infty 20}$	Avg. K_La_{20}	Avg. SOTE	Avg. SOTE per ft of submergence[d]						
		(SCFM)	(mg/L)	(1/h)	(%)	(%)						
Membrane		1	10.114	5.37	25.752	1.717						
Membrane		2	10.288	14.78	35.868	2.391						
Membrane		3	10.252	27.148	43.906	2.927						
Ceramic		1	10.556	10.499	52.886	3.526						
Ceramic		1.5	10.551	20.419	67.035	4.469						
Ceramic		2	10.116	17.423	41.225	2.748						
HDPE		1.5	10.536	14.738	47.954	3.197						
HDPE		3	10.419	25.404	41.747	2.783						

a Probe 1 is the upper DO probe in the aeration column and probe 2 is the lower DO probe.
b SCFM is standard cubic feet per minute
c HDPE is high-density polyethylene.
d The diffuser submergence is 15 ft.

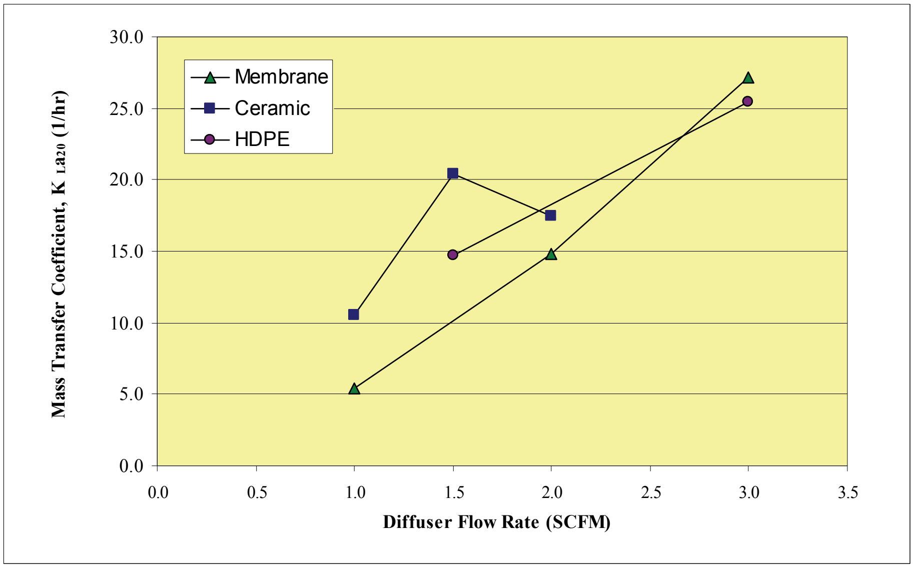

Figure 7.1. Average mass transfer coefficient from clean water tests on three fine-pore diffusers.

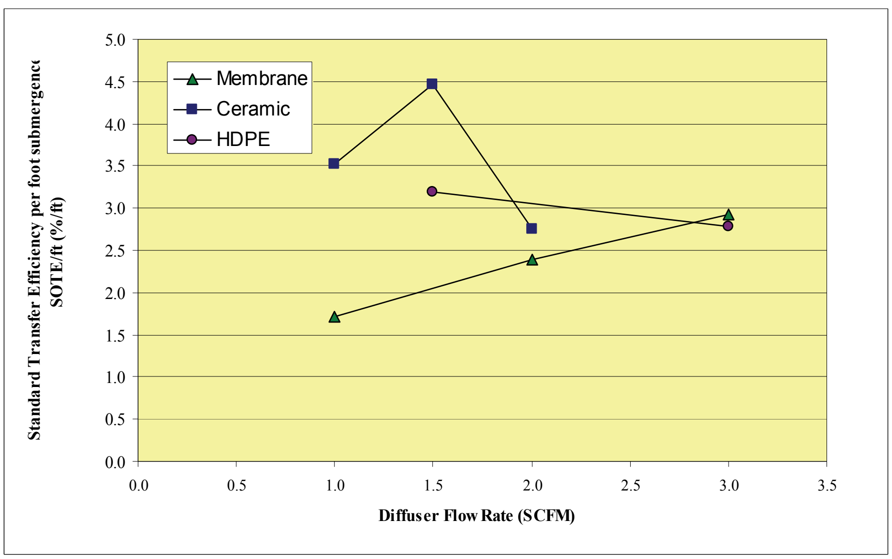

Figure 7.2. Average standard OTE per foot of submergence from clean water tests on three fine-pore diffusers.

Following off-gas tests in mixed liquor ranging from 3 to 18 g/L, α values were computed. The computed α values are compared in Table 7.2 for the three different fine-pore diffusers. It can be observed that under air flow rates of both 1 SCFM and 2 SCFM, the α value of the membrane diffuser is consistently higher than that of the ceramic diffuser at each MLSS. And under an air flow rate of 1.5 SCFM, the α value of the HDPE diffuser is always higher than that of the ceramic diffuser at each MLSS. In addition, the α value of membrane diffuser under an air flow rate of 1 SCFM is higher than that of the HDPE diffuser at each MLSS. Figure 7.3 shows the relationship between α values and MLSSs during the study.

Table 7.2. Comparison of α values for three different diffusers[a]

MLSS (mg/L)	AFR (SCFM)	*α* (Membrane)	*α* (Ceramic)	AFR (SCFM)	*α* (Membrane)	*α* (Ceramic)	AFR (SCFM)	*α* (Ceramic)	*α* (HDPE)
3082	1	0.32	0.04	2	0.58	0.40	1.5	0.16	0.27
3867	1	0.53	0.17	2	0.36	0.27	1.5	0.16	0.19
5436	1	0.22	0.09	2	0.21	0.21	1.5	0.12	0.16
8367	1	0.19	0.13	2	0.29	0.27	1.5	0.13	0.18
10,533	1	0.17	0.09	2	0.17	0.14	1.5	0.08	0.11
11,967	1	0.16	0.09	2	0.14	0.12	1.5	0.07	0.10
14,760	1	0.14	0.06	2	0.11	0.09	1.5	0.05	0.08
17,667	1	0.12	0.05	2	0.09	0.08	1.5	0.05	0.05

[a] AFR, air flow rate.

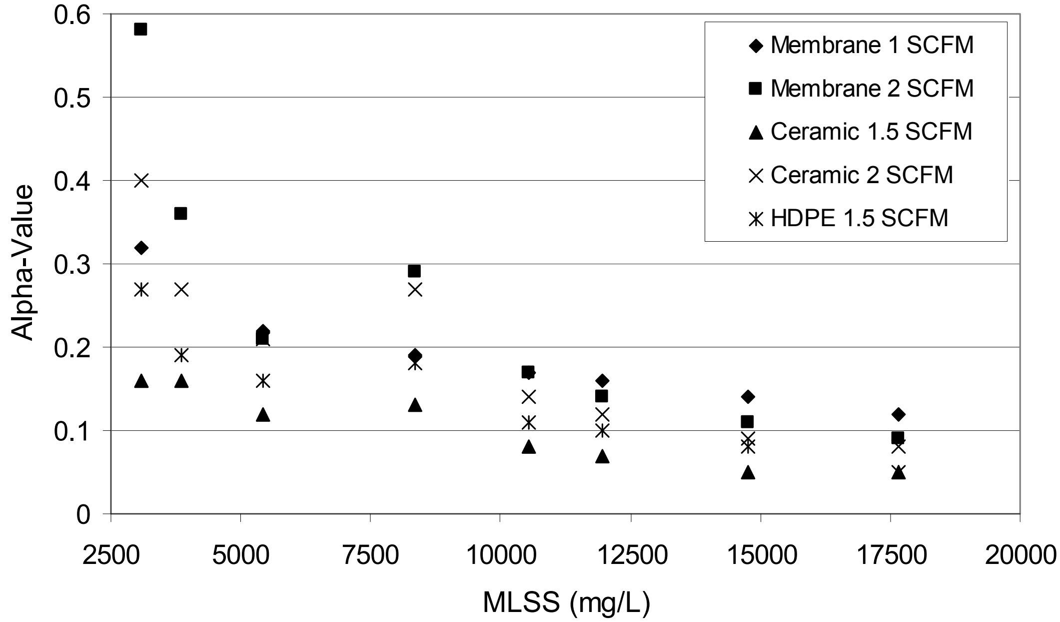

Figure 7.3. Comparison of α values at different MLSS values.

The results for each diffuser at various air flow rates showed the expected tendency, which is for α values to increase with MLSS. The only exception occurred with the ceramic diffuser under 1 SCFM. No dependence of α value on MLSS or MLVSS was observed under that condition. Figure 7.4 shows the correlation between MLSS and α value. The regression coefficients (R^2) of the curves were 0.94 (membrane, 1 SCFM), 0.87 (membrane, 2 SCFM), 0.93 (ceramic, 1.5 SCFM), 0.89 (ceramic, 2 SCFM), and 0.93 (HDPE, 1.5 SCFM). Figure 7.5 shows that the viscosity of activated sludge is linearly dependent on MLSS.

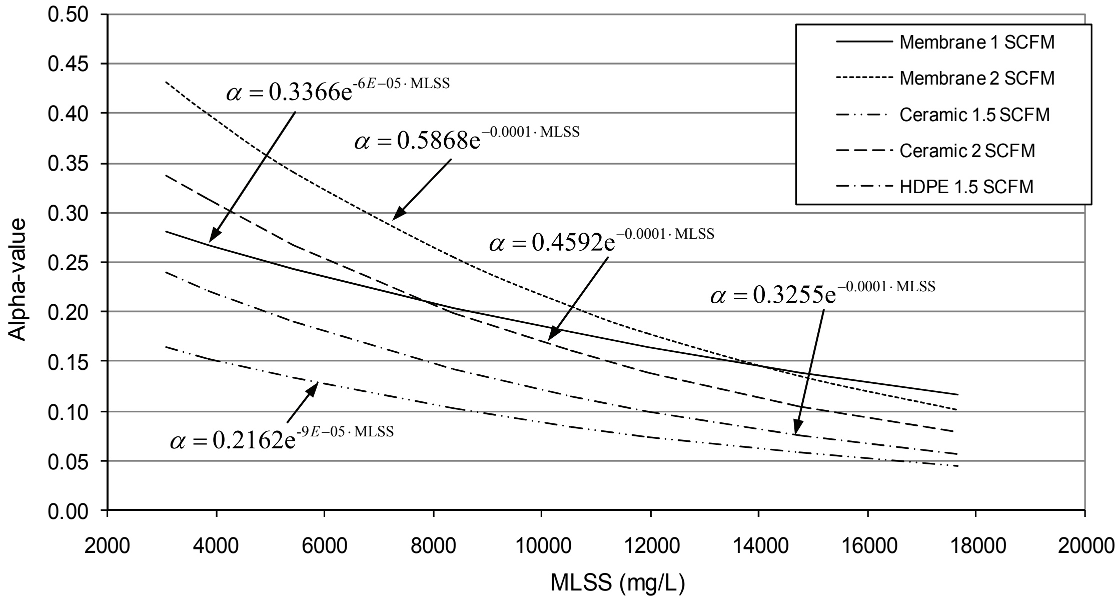

Figure 7.4. Correlation of MLSS and α value.

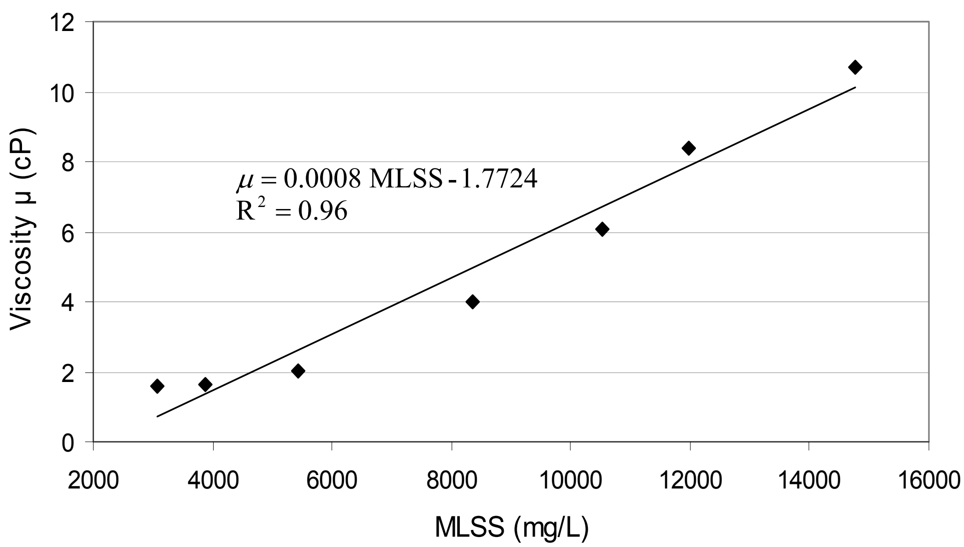

Figure 7.5. Correlation of MLSS and viscosity.

As shown in Figure 7.6, as viscosity increased, the α value decreased under different process conditions during this study. However, no dependence of α value on viscosity was observed with the ceramic diffuser under an air flow rate of 1 SCFM.

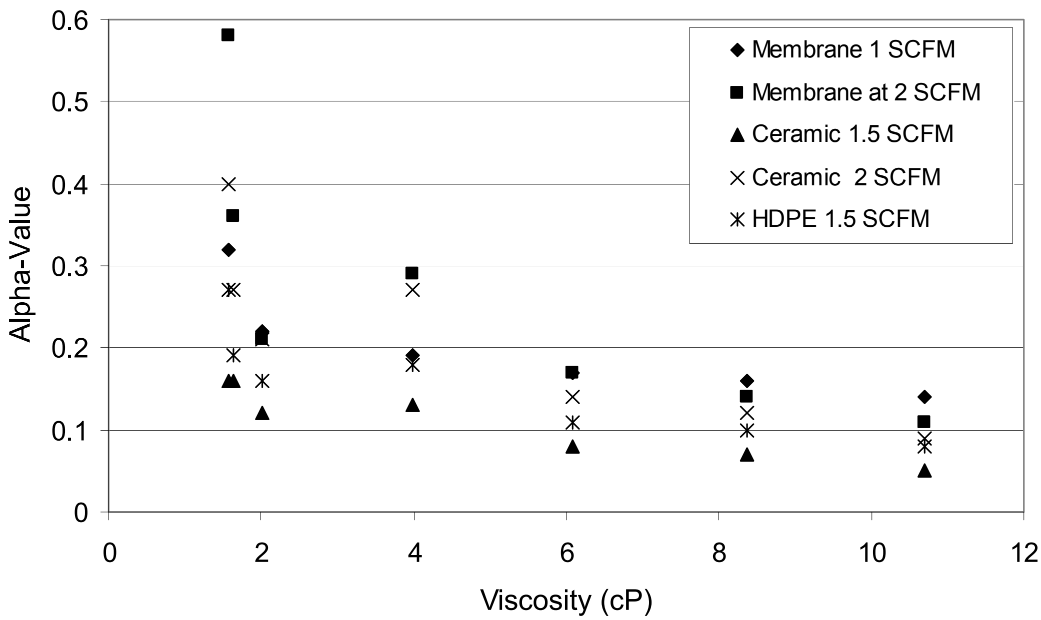

Figure 7.6. Comparison of α value with viscosity.

The correlation between α value and the viscosity for each diffuser at each air flow rate is shown in Figure 7.7. The regression coefficients (R^2) of the correlating curves were 0.79 (membrane, 1 SCFM), 0.76 (membrane, 2 SCFM), 0.94 (ceramic, 1.5 SCFM), 0.85 (ceramic 2, SCFM), and 0.86 (HDPE, 1.5 SCFM), respectively.

Figure 7.8 shows a correlation between oxygen uptake rate (OUR)and MLSS. The OUR was found to be an important factor influencing α values during the study. As shown in Figure 7.9, decreasing α values were observed at increasing OUR except for the ceramic diffuser under an air flow rate of 1 SCFM.

In Figure 7.10, α value and the OUR were correlated for each diffuser under different air flow rates. The regression coefficients (R^2) of the correlating curves were 0.88 (membrane, 1 SCFM), 0.91 (membrane, 2 SCFM), 0.90 (ceramic, 1.5 SCFM), 0.92 (ceramic, 2 SCFM), and 0.83 (HDPE, 1.5 SCFM), respectively. The OUR of activated sludge is a suitable factor for estimating the α value.

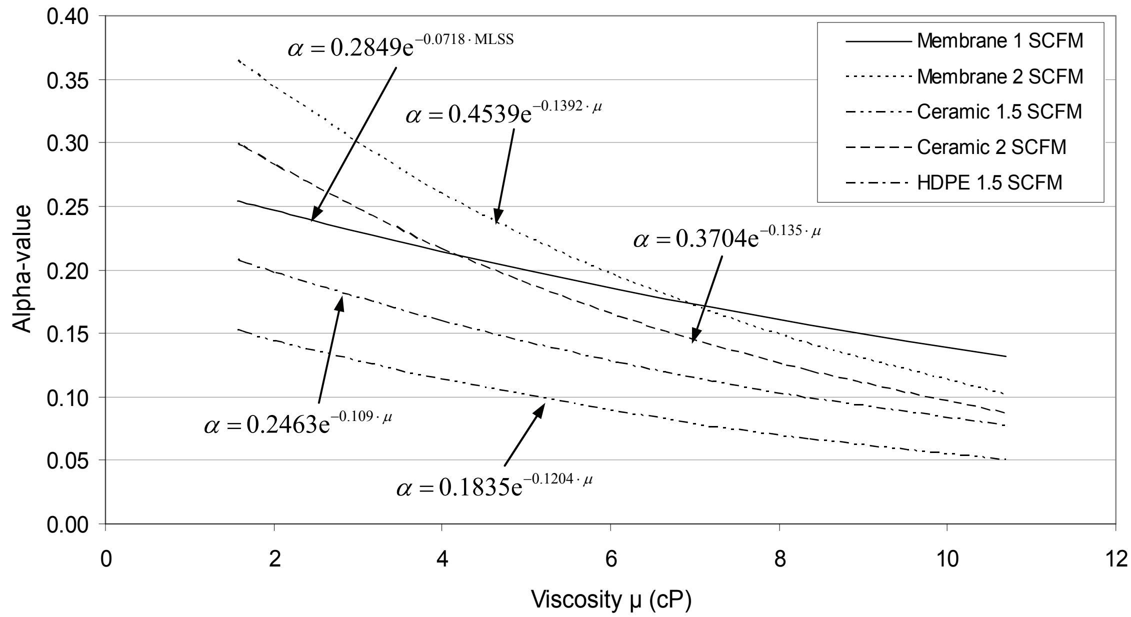

Figure 7.7. Correlation of viscosity and α value.

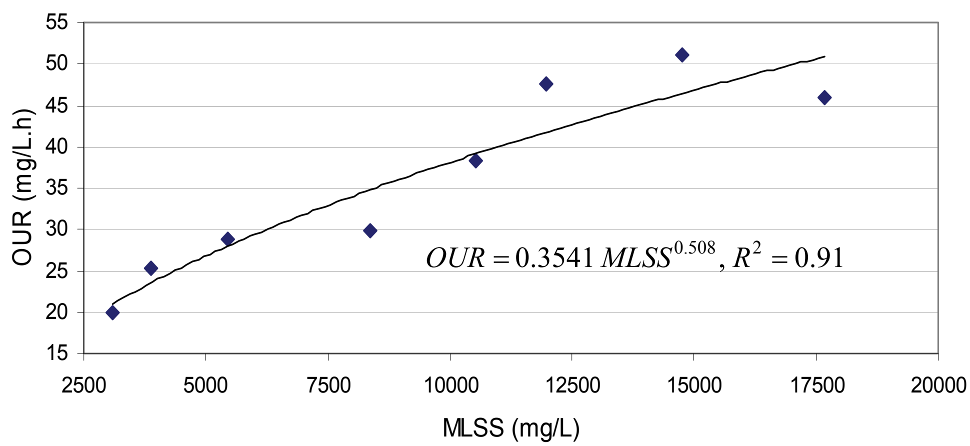

Figure 7.8. Correlation of OUR and MLSS.

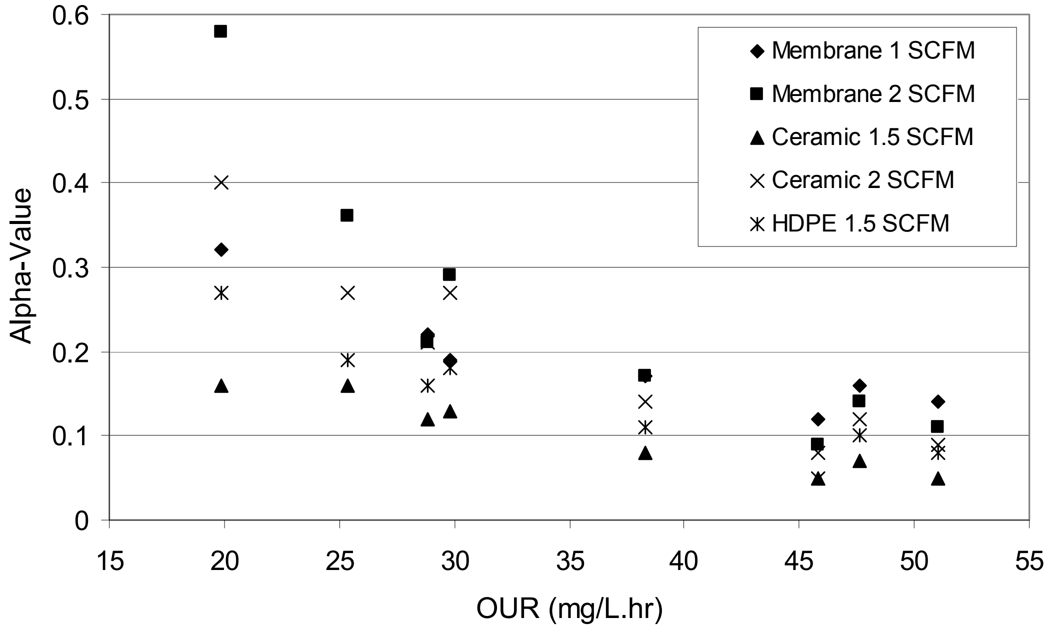

Figure 7.9. Comparison of α values under different process conditions via OUR.

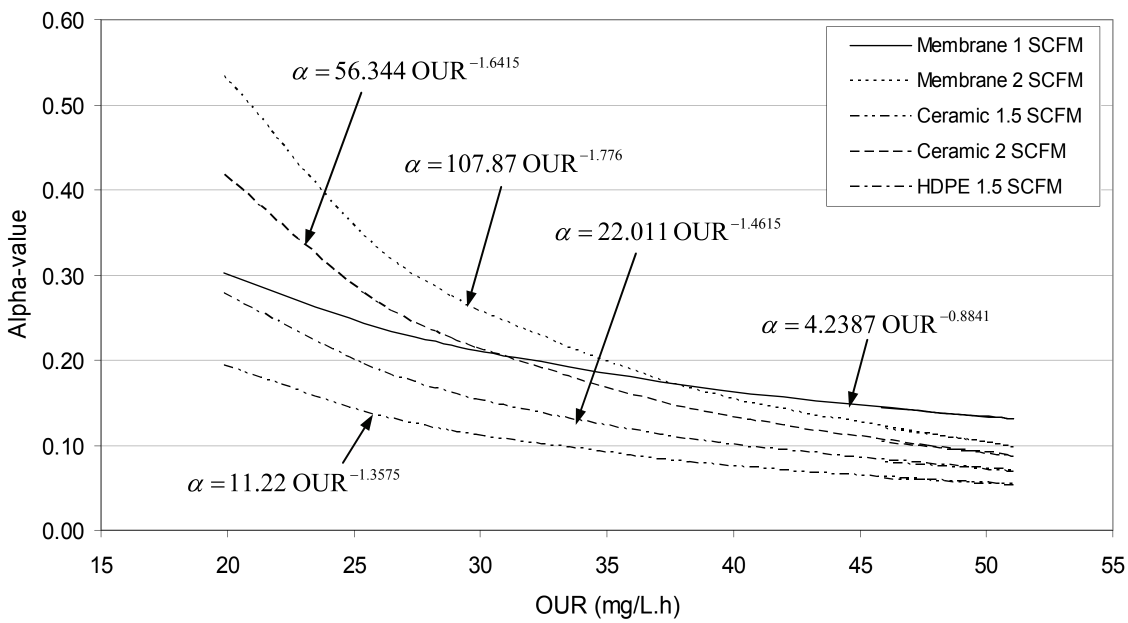

Figure 7.10. Correlation of OUR and α value.

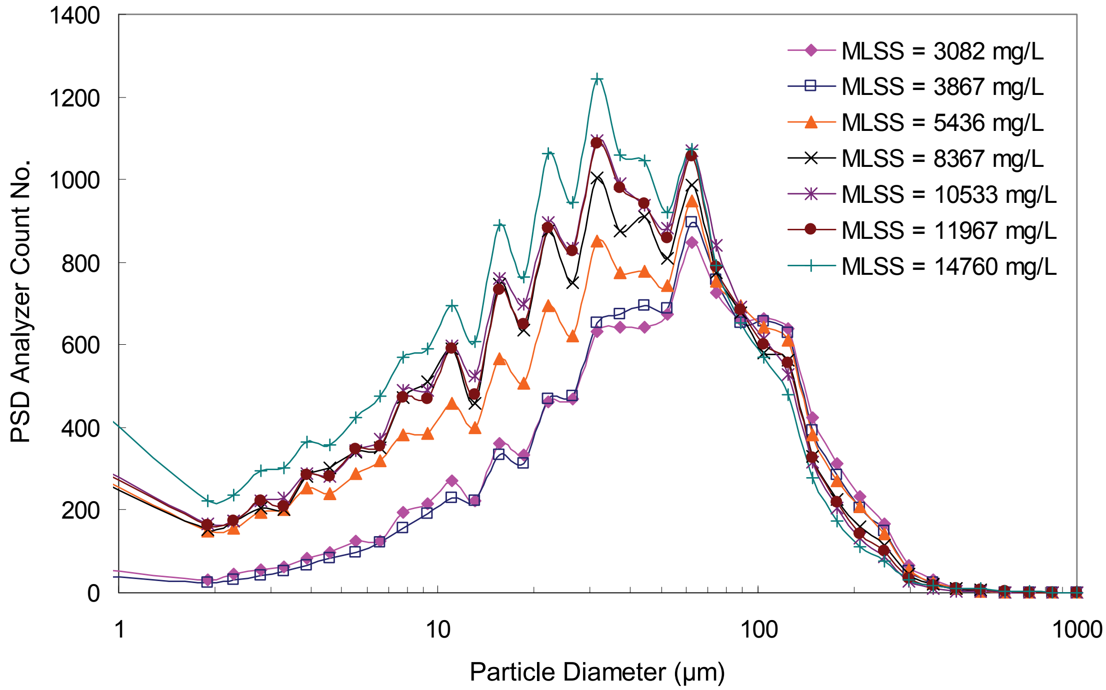

Figure 7.11. PSDs at various MLSSs.

The PSD of activated sludge mixed liquor at various concentrations was investigated in the range of 0.8 to 1000 µm. As shown in Figure 7.11, the PSDs of the different activated sludges were similar, with the median particle size generally decreasing as MLSS increased. The relationship between the median particle size and MLSS is depicted in Figure 7.12.

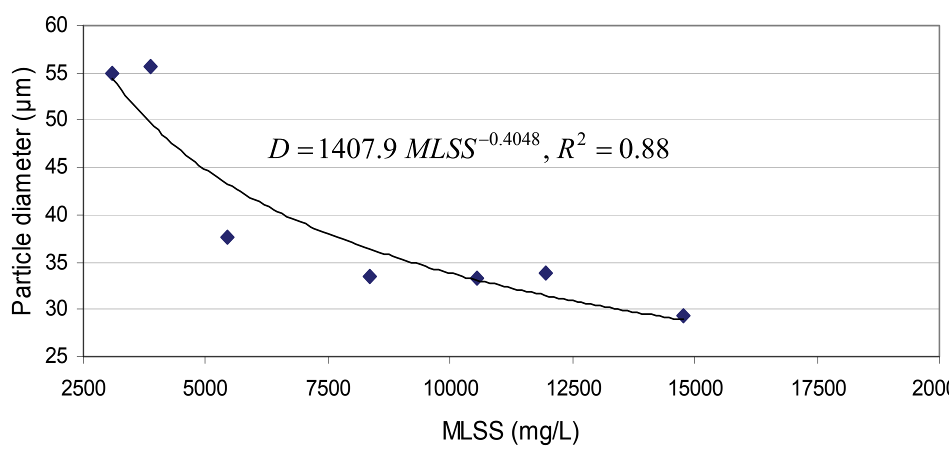

Figure 7.12. Correlation of particle size and MLSS.

The relationship between α value and median particle size is shown in Figure 7.13. It was observed that α values increased with particle size, except for the ceramic diffuser under an air flow rate of 1 SCFM.

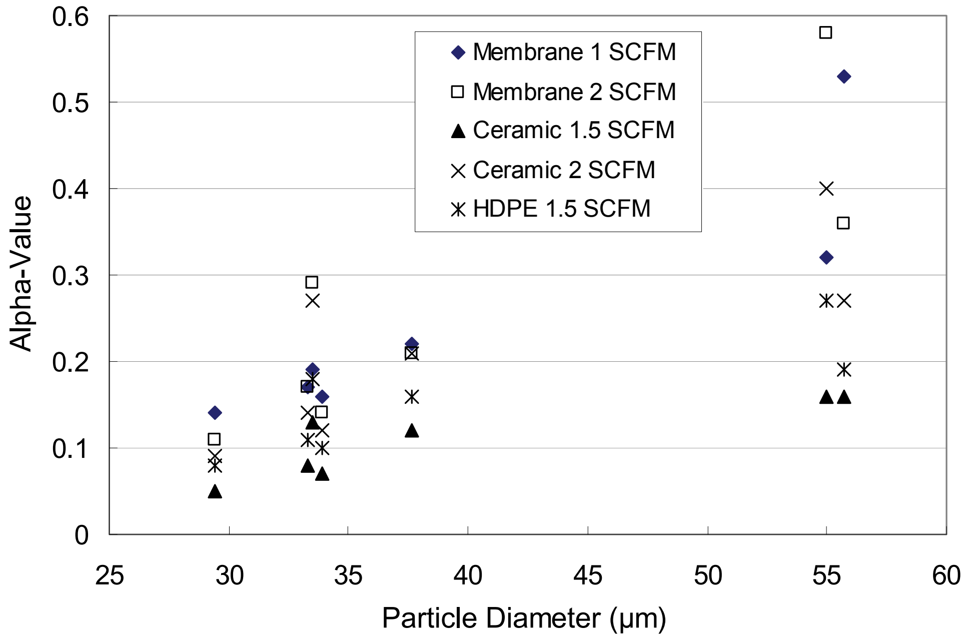

Figure 7.13. Comparison of α values under different process conditions via particle size.

The measured total SMP, total EPS, SCOD, and TDS values for different concentrations of mixed liquor were examined for any correlation with α values. No correlations were discovered for these parameters in this study.

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 PERFORMANCE COMPARISON OF SIX PILOT MBRs

A large number of water quality data were collected in this study. The object of this data collection was to demonstrate the consistency of treatment effectiveness across different MBR configurations and for different waste streams. There were relatively few data in the literature for multiple MBR configurations treating the same wastes under the same nonoptimal conditions simultaneously. This is not the same as shootout competition, in which the objective is to select a single MBR vendor for procurement purposes. In that case, with more at stake, the test protocol must be established to allow comparisons that affect full-scale design and, most important, cost. This was a different type of pilot test. It was more of a demonstration designed to test the technology and give some of the newer, smaller systems a chance to operate next to the industry leaders. In any side-by-side test, comparisons are inevitable and appropriate. However, it is important to note the types of information that can and cannot be gained from this test. It is not correct to determine the "best" MBR from these tests. These pilot MBRs were all operated under slightly different sets of nonoptimal conditions, and they were not coddled. For the most part, the units were set to operate and see what would happen. Along the way, observations were made regarding their manner of operation, the degree of complexity, cleaning requirements, etc.

The six MBRs were of very different configurations in terms of membrane materials, membrane pore sizes, membrane shape, aeration rates, bioreactor configurations, and other parameters. In spite of these differences, there were important similarities as follows:

- Each of the six pilot MBRs produced very similar, very-high-water-quality permeate with reliability.
- Permeate water quality was excellent—far superior to that of conventional activated sludge effluent and to medium-filtered tertiary effluent in terms of conventional parameters such as BOD (<3 mg/L), TSS (<2 mg/L), turbidity (mostly <0.1 NTU), indicator organisms (<1 CFU/100 mL), and UVT (>70%).
- MBR permeate is suitable for disinfection with UV radiation, since it is compact and does not require a chemical supply train or involve handling and storage issues.
- MBRs can operate reliably under various strength conditions due to extended SRT in a smaller footprint.

Operation and maintenance observations common to all of the six MBR pilot units are as follows:

- MBR operations are highly automated and controllable but not maintenance free.

- MBRs are easy to operate; however, skilled operators who understand activated sludge, membrane filtration, and automation are needed.
- Periodic recovery cleaning is necessary but easy and effective (chlorine, 2000 ppm; hydrochloric acid, 1%). Cleaning was required after polymer dumps, power outages, equipment failures, and each phase of testing.
- Many screenings were obtained with the 0.5-mm-pore-size screen, compared to the 3-mm-pore-size screen.
- The MBRs operated at the flux rates advertised: 10 or 15 GFD.
- TMP was a good indicator of the need to recovery clean the membranes.

The effects of this study in Hawaii included increased interest in the MBR process and consideration or evaluation of MBRs for many development projects, upgrade projects, and decentralized treatment projects. As of the end of 2006, only one full-scale MBR system had been constructed and put into service in Hawaii. This is a relatively large, 4-MGD system at SBWWTP. It is likely that this study helped facilitate that project and that many more projects will follow as well.

8.2 PERFORMANCE OF PAD-K MEMBRANE THICKENER/DIGESTER

The results of these pilot tests with the Enviroquip in PAD-K mode were mixed. There were difficulties due to the nature of the waste sludge, which was not MBR sludge. Because the sludge had a young sludge age of 5 days, it had both a high volatile content and high nitrogen content (ammonia and organic forms). These constituents resulted in an excessive aeration requirement that was not achievable. Under these conditions, there was buildup of ammonia leading to nitrogen poisoning and membrane fouling. The lessons learned from this pilot test included the follwoing:

- With low SRT sludge feed from non-MBR systems, it is possible to meet volatile-solid reduction requirements, but effective nitrification and denitrification are needed for stable, continuous operation.
- When high nitrogen conditions occur, high SMP concentrations will result, leading to high TMP fouling.

However, it is a good idea to use membranes for sludge thickening in certain circumstances, mainly for smaller MBR facilities and possibly those with limited operations staff. The thickeners can function continuously without chemical addition and without staffing (unlike more-efficient unit operations such as centrifuges and filter presses) and may be more efficient and definitely produce less odor than gravity thickeners. In many cases this may be an efficient use of “used” MBR membrane cassettes that are no longer able to permeate at design flux rates and can be de-rated and used for thickening operations rather than going directly to a landfill.

8.3 SELECTION CRITERIA FOR MBR SYSTEMS

This project developed criteria to assist designers and owners in the selection of MBR equipment. Although permeate water quality is essentially the same for all of the six

MBRs evaluated, there are differences between the equipment that can be grouped into cost and noncost factors as follows:

- Cost issues include membranes and configuration, power and chemical usage, redundancy provisions, pretreatment needs, equipment durability, redundancy, and materials of construction.
- Noncost factors include ease of operation; control complexity; cleaning frequency, modes, and complexity; and company profiles and experience.

In addition, there can be site-specific requirements that could help narrow the selection pool such as

- Complexity—remote operation
- Electricity costs
- Number of screenings produced
- Design flux as it relates to the magnitude of peak flows

In general, the designer should use a prequalification process that considers life cycle costs (including warranty duration and membrane replacement costs) and noncost factors. The presence of multiple vendors ensures good price competition. MBRs are an excellent technology that is relatively mature but still subject to innovation, and designers should be conservative in terms of flux design to maximize membrane life. These systems are not operation free or maintenance free.

8.4 EVALUATION AND CONTROL OF MEMBRANE FOULING

Membrane fouling is a complex and as yet poorly understood phenomenon with many causes and potential control methods. Most current MBR research is aimed at evaluating membrane-fouling mechanisms in the pursuit of control methods. In this study, preliminary efforts have been made to evaluate fouling monitoring methods and to seek correlations with operating and environmental conditions. This study looked at critical flux determinations, fouling resistance components, fouling rates, SMP, EPS and their potential relationships with SRTs, PSDs, viscosity, colloidal TOC, and other parameters. This study also included preliminary efforts to investigate and compare the bacterial diversity in MBR biofilms and in MBR bulk liquor in relation to membrane-fouling rates and water quality parameters such as EPS and SMP. No conclusions are available at this time, and additional work is recommended below.

8.5 DESIGN OF FINE-PORE AERATION SYSTEMS FOR MBRs

The design of fine-pore aeration systems for activated sludge systems in general is highly dependent upon the α factor. The α factor is the ratio of the mass transfer coefficient in process water to the mass transfer coefficient in clean water. It is influenced by several factors and is reduced in activated sludge systems with elevated suspended-solid concentrations such as MBRs. The α factor may be reduced by as much as 50% at 15 g/L of mixed liquor/L compared to 2.5 g/L. This would mean that twice as many diffusers and twice as much air would be required to transfer the same amount of oxygen into the water in an MBR. The results of this study provide guidance to designers on the appropriate magnitude of the α value to use for design of MBR aeration systems. Here, α

was found to be mostly correlated to viscosity, as expected. Unfortunately no new relationships were discovered between the α value and and other parameters such as SMP, EPS, particle size distribution or other factors.

8.6 MBR APPLICATIONS AND FACILITY PLANS FOR OAHU

A study was conducted to examine possible applications of MBRs for decentralized production of recycled water on the island of Oahu. The objectives of this study were to identify potential reuse and treatment facility sites and to develop costs to build and operate these facilities. Eight sites were preliminarily identified from the potential top 100 water users' list as potential locations for MBR water recycling facilities:

- Central Oahu Regional Park
- Public Bath Wastewater Pump Station and Ala Wai Golf Course
- Sand Island Wastewater Treatment Plant
- Moana Park Wastewater Pump Station
- Kailua Beach Park
- Kamehameha Highway Wastewater Pump Station
- Fort DeRussy Wastewater Pump Station
- University of Hawaii at Manoa

Cost estimates were developed for 0.1-, 0.25-, 0.5-, and 1.0-MGD installations to help bracket anticipated flow rates. These estimates include capital and operational costs for the MBR process and UV disinfection. For the decentralized systems, the facilities are strategically located near the wastewater source and the sludge is returned to the sewer. Therefore, costs for conveyance piping and sludge disposal are not included. Also, we assume that the user provides a storage tank and do not consider the cost of storage.

8.7 RECOMMENDED FUTURE WORK

The most important future research related to MBRs will have to investigate membrane fouling since it affects both initial capital costs and later operating and maintenance costs. There is a need for better understanding of biofouling in MBRs and of methods to control said fouling in order to improve the economics of water recycling. There is also a need to catalog the types and quantities of biofilm organisms, bulk flocculating organisms, and filamentous organisms in MBRs. Comparisons should be made between conventional systems and MBRs operated under conditions subject to change, such as flux rate, hydraulic retention time, SRT, organic/nutrient loading, and state of oxygenation (high, low, anoxic, or anaerobic). Correlations are needed between microorganisms and biofouling and various parameters such as TMP, biofilm thickness, SMP, EPS, viscosity, PSD, soluble COD, and filterability. It may be possible to correlate microorganism population dynamics with biofouling conditions and system operating conditions. Through the control of biofouling, MBRs, which are already becoming an industry standard for water recycling, can be made more reliable and cost effective.

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