Operation of a Submerged Hollow Fiber Membrane Bioreactor for Wastewater Treatment on Meeting Reclamation Criteria

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ABSTRACT

Title 22 of the California Health and Safety Code of Regulations establishes the criteria for water quality and treatment reliability related to use of reclaimed water. Hydranautics/Mitsubishi Rayon Engineering conducted a pilot study to verify that the filtrate of the HYDRAsub®/Sterapore SADF®-MBR meets the Title 22 criteria (no higher than 0.2 NTU more than 5% of the time within a 24-hour period and 0.5 NTU at any time) under average and peak fluxes. This study was also conducted to benchmark the virus removal by the HYDRAsub®-MBR and to minimize capital and operating cost through optimization of average and peak fluxes.

INTRODUCTION

The California Department of Public Health (CDPH) has established specific criteria for water quality standards and treatment reliability related to the use of reclaimed water in Title 22 of the California Health and Safety Code of Regulations. *§60301.320* of Title 22 of the California Health and Safety Code of Regulations requires that wastewater that has been passed through a microfiltration, ultrafiltration, nanofiltration, or reverse osmosis membrane should have filtrate turbidity that does not exceed 0.2 NTU more than 5 percent of the time within a 24-hour period and 0.5 NTU at any time. All membrane filters which are to be used for domestic wastewater reclamation must first be approved by the CDPH. To gain approval, the CDPH requires that a pilot study be conducted to verify that filtrate in accordance with the above Title 22 requirements.

In addition to the turbidity requirements described above, Title 22 states that reclaimed wastewater that uses a disinfection process other than chlorination must achieve 5-log polio virus or MS2 inactivation/removal when combined with a filtration process. The test is also used to benchmark the level of virus removal to determine the amount of further disinfection required.

From February 2009 to May 2009, Hydranautics and Mitsubishi Rayon Engineering (MRE), along with the help of HDR Engineering, executed a CDPH approved pilot study protocol to verify that Hydranautics' HYDRAsub-MBR® membrane, also known as MRE's Sterapore-SADF®, is capable of meeting the Title 22 requirements for membrane filtered wastewater reuse. The membrane will be referred to as HYDRAsub®/Sterapore-

SADF® for the remainder of this document. The pilot study was conducted at the South Orange County Wastewater Authority's (SOCWA) Plant 3A, located in Laguna Niguel.

MATERIALS AND METHODS

Feed Water Quality

For the duration of the pilot study, the feed water to the pilot system was effluent from the primary clarifier at the South Orange County Wastewater Authority's (SOCWA) Plant 3A. As described in more detail below, primary clarifier effluent was screened before entering the anoxic tank of the MBR pilot system. Screened primary clarifier effluent shall be referred to as MBR influent for the remainder of this document. Water quality for the MBR influent is given in Table 1.

Table 1: MBR Influent Water Quality

Parameter	Units	Number of Analyses	Median	Minimum	Maximum
TKN	mg/L-N	21	66	55	130
Ammonia - N	mg/L-N	21	49	37	100
Nitrate - N	mg/L-N	11	ND[1]	ND[1]	0.19
Nitrite - N	mg/L-N	11	ND[2]	ND[2]	0.37
BOD_5	mg/L	5	140	120	190
COD	mg/L	19	320	53	440
TSS	mg/L	19	62	42	100

1. Method detection limit (MDL) for nitrate is 0.11 mg/L; nine of 11 samples were non-detect (ND).
2. MDL for nitrite is 0.15 mg/L; nine of 11 samples were ND.

Pilot Unit Description

The MBR pilot system used during testing was designed by Hydranautics, MRE, and HDR to test the HYDRAsub-MBR®/Sterapore SADF® membranes. Because requirements for nitrogen removal from wastewater are becoming common, the pilot system design was based on the Modified Ludzack-Ettinger (MLE) process for nitrogen removal, as shown in Figure 1. Figure 2 shows the actual arrangement of the pilot system.

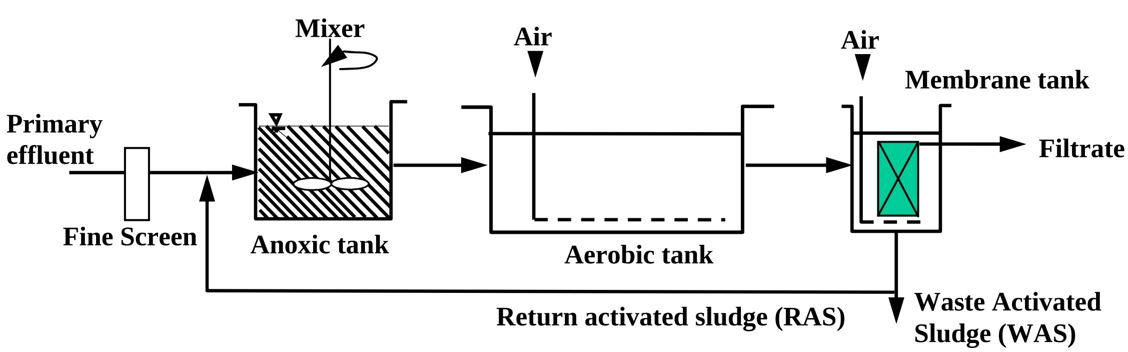

Figure 1: HYDRAsub®/Sterapore SADF® Title 22 Certification Pilot System Process Flow Diagram

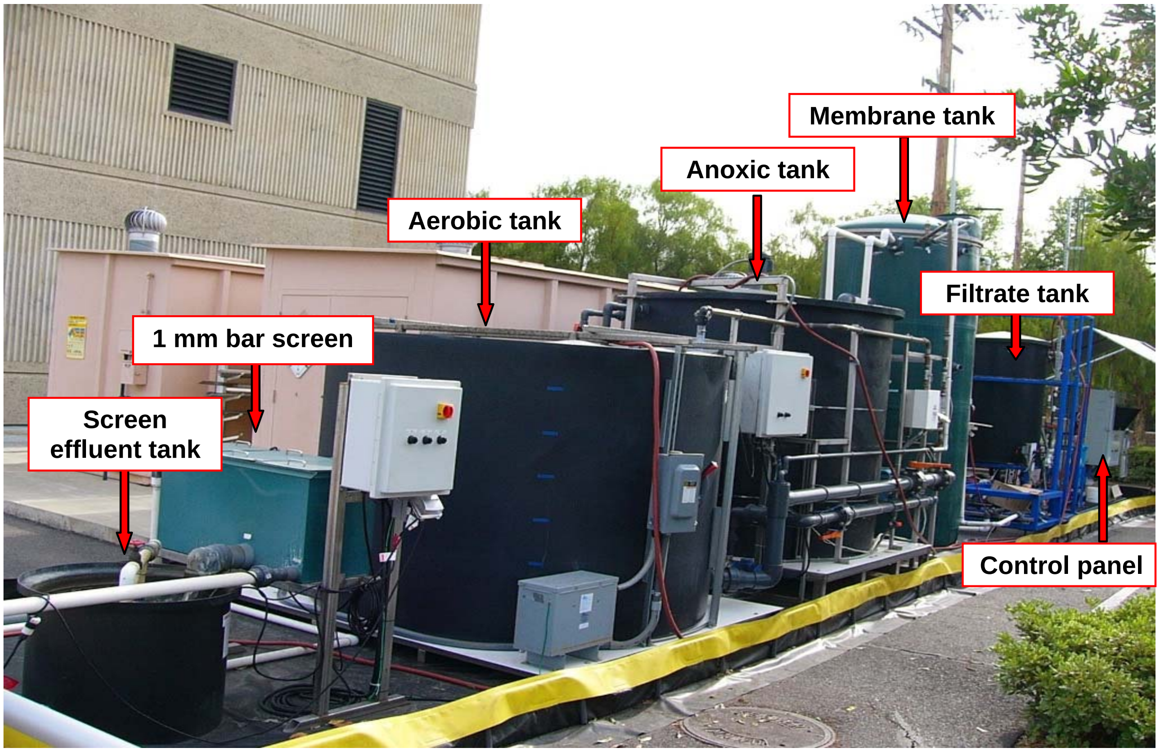

Figure 2: HYDRAsub®/Sterapore SADF® MBR Title 22 Certification Pilot System

Throughout testing, large particles and fibrous materials, which could damage the membranes, were removed from the primary clarified effluent by a self cleaning bar screen with 1 mm openings, which is shown in Figure 2.

The bar screen effluent was then collected in a 150 gallon tank and pumped to the anoxic tank. As shown in Figure 3, the anoxic tank was equipped with a top entry mixer to keep the suspended solids well mixed.


Figure 3: Anoxic Tank

As shown in Figure 1, MBR influent was combined with return activated sludge (RAS) in the anoxic tank. Following anoxic treatment, activated sludge, or mixed liquor, then overflowed to the aerobic tank (shown in Figure 4) where oxygen was supplied via fine bubble diffusers.


Figure 4: Aerobic Tank

Following aerobic treatment, the mixed liquor was pumped to the membrane tank. As previously mentioned, the membrane in an MBR is used for solid-liquid separation. The membrane filtrate was collected in a 400 gallon tank. The separated suspended solids remained in the mixed liquor and continued to recirculate throughout the system, overflowing from the membrane tank to the anoxic tank.

The key tank volumes and hydraulic retention times are summarized in Table 2.

Table 2: HYDRAsub®/Sterapore SADF® MBR Title 22 Certification Pilot Tank Summary

	Aerobic tank	Anoxic tank	Membrane tank	Total
Volume, m^3 (gal)	1750	1300	1900	4950
HRT at design flow, hr	3.0	2.2	3.3	8.6
HRT at peak flow, hr	2.0	1.5	2.2	5.6

HYDRAsub®/Sterapore SADF®-MBR Process Description

Operating Sequence

HYDRAsub®/Sterapore SADF®- MBR membranes are vertically oriented, outside-in, hollow fiber, PVDF, submerged microfiltration membranes. During filtration, a suction pressure is applied to the filtrate side (the inside) of the membrane fibers. The suction pressure is usually created through the use of a self-priming centrifugal pump. The suction pressure pulls water to the inside of the fibers, leaving particulate matter on the feed side (the outside) of the fiber. As solids accumulate on the feed side of the membrane fibers and in the membrane pores, more suction pressure is required to maintain a constant flow rate. The difference between the pressure on the feed side of the membrane and the filtrate side of the membrane is called the transmembrane pressure, or TMP. The TMP is the primary measure of membrane fouling. To maintain low TMP and prevent solids accumulation on the feed side of the membrane fibers, air is continuously supplied to a coarse bubble air diffuser located below the membranes. Coarse bubbles, generated by the diffuser, rise through the membrane fiber bundles, creating a scouring effect which limits the amount of solids deposition on the outer membrane surface and pore plugging, thereby helping to maintain a low TMP.

After a set amount of filtration time, the membranes enter a relaxation step, or soak step. During the relaxation step, filtration stops while coarse air bubbles continue to create a scouring effect to remove extraneous particulate matter from the feed side of the membrane which may have been accumulated during filtration.

Over time, some accumulated particulate matter (or foulants) on the membrane and in the pores may not be removed by the relaxation step. To remove this portion of foulants, a weekly chemically enhanced backwash is utilized. During the chemically enhanced backwash, aeration stops, then a low concentration of chlorine solution is injected to the filtrate side of the membranes at a low flux for a set amount of time. The chlorinated solution soaks in the membrane fibers and pores, breaking down any foulants that were not removed by normal aeration. Following the injection period, aeration is restarted, which removes the accumulated foulants. Normal operation resumes after a short aeration period.

HYDRAsub®/Sterapore SADF®-MBR Module and Element Description

For this pilot study, a specially designed HYDRAsub®/Sterapore SADF® module with a total active membrane area of 75 m^2 (HSM75) was used. A HYDRAsub®/Sterapore SADF® module is comprised of the membrane elements, coarse air diffuser, filtrate adapters and supporting cage. Figure 5 shows the standard HYDRAsub®/Sterapore SADF® module, which is referred to as a HSM500. The main difference between the HSM75 and HSM500 is the number of elements. The HSM500 has twenty HYDRAsub Element-25 m^2 (HSE25), while the HSM75 has only three. Figure 5 also displays the HSE25. Filtrate is drawn through both ends of the large diameter supported PVDF hollow fiber membranes, which are soft potted in the HSE25.

Figure 5: HYDRAsub Module - 500 m^2 (HSM500), left. HYDRAsub Element – 25 m^2 (HSE25), right.

Analytical Methods

On-site Analysis

The pilot unit was equipped with a PLC and HMI to automate the operating sequences described above and to collect operating data. The HMI automatically recorded the following data:

Table 3: Automatically Recorded Data

Parameter	Instrumentation Type	Location	Frequency
Temperature	GF Signet 2350 Temperature Sensor	Filtrate pipe	1 data point/5 minutes
Filtrate flow rate	GF Signet 515 Rotor-X Flow Sensor		
Filtrate pressure	Parker MPS-3 Pressure Sensor		
Wasted sludge flow rate	GF Signet 515 Rotor-X Flow Sensor		
Filtrate turbidity	Hach 1720E Low Range Turbidimeter		

As described in the introduction, the key parameter for Title 22 approval is the filtrate turbidity. To ensure the accuracy of the filtrate turbidity readings, the Hach 1720E Low Range Turbidimeter was calibrated according to the manufacturer's 2-point calibration protocol at the beginning of the testing period and again after three months of operation, which is more frequently than specified by the manufacturer.

Automatically recorded data was downloaded from the HMI and analyzed. Flux can be calculated according to Equation 1. TMP can be calculated according to Equation 2.

$$J_{\text{filtrate}} = \left(\frac{\frac{L_{filtrate}}{hour}}{m^2 \;_{\text{active membrane filtration area}}} \right)$$

Equation 1

$$P_{TMP} = P_{gauge} + \Delta P_{height}$$

Where,

ΔP_{height} = altitude difference between the location of the pressure gauge and the average water level in the membrane tank, in terms of pressure.

Equation 2

In addition to automatically recorded data, Hydranautics and MRE staff manually collected data with handheld instruments to verify the accuracy of the instrumentation.

Off-site Analysis

HDR arranged for samples of the MBR influent and effluent to be analyzed by an outside laboratory, Test America. Test America measured the COD, BOD, TSS, TKN, and NH4 of samples collected from the MBR influent and effluent.

Hydranautics and MRE staff also regularly measured the MLSS and MLVSS according to the Standard Methods 2540D and 2540E, respectively(APHA, 1998).

Virus Testing

To benchmark the virus removal capability of the HYDRAsub®/Sterapore SADF® MBR membranes, influent and effluent concentrations of a virus surrogate, MS2 bacteriophage, were measured at three different fluxes: 33.1 LMH for 24 hours, 50.1 LMH for 4 hours, and 45.4 LMH. In all tests, the procedure was the same. The virus surrogate, MS2 bacteriophage, was seeded to the aerobic tank. At the same time, filtration was stopped. The sludge was then circulated from the aerobic tank to the anoxic tank and back to the aerobic tank for 16 hours, bypassing the membrane tank. This was done to allow the virus concentration to reach equilibrium in the system before starting filtration. Following the equilibration, filtration resumed at the above fluxes.

RESULTS

HYDRAsub®/Sterapore SADF® MBR Membrane Performance Results

Flux and TMP

From the beginning of March 2009 to the end of April 2009, the official Title 22 testing was conducted. Prior to this time, there was a startup period in which the mixed liquor suspended solids (MLSS) was built up to the optimal range. Figure 6 shows the main membrane performance operating parameters: flux, TMP, and water temperature.

From March 3rd to April 13th, the HYDRAsub®/Sterapore SADF® MBR membranes were operated at an instantaneous flux of 33.1 LMH (19.6 gfd). At this flux, the TMP averaged 10.1 kPa, with a range of 2 and 15 kPa. Daily fluctuations in the TMP were most likely a result of changes in the temperature. As the temperature increased, the viscosity of the sludge decreased, so the pressure required to pull filtrate through the membranes (or TMP) decreased. The opposite was true as the sludge temperature decreased. Although there is a clear correlation between the TMP and the sludge temperature, the data presented in Figure 6 has not been temperature corrected. As temperature changes in the activated sludge, not only the viscosity changes; biological processes also change. Therefore, it is inappropriate to put a viscosity based temperature correction on the data. Due to the stable TMP observed at 33.1 LMH, Hydranautics and MRE staff decided to operate at an increased filtrate flux of 38.0 LMH (22.5 gfd) from April 13th to April 28th. At this flux, an average TMP of 12.3 kPa was observed, with a range of 5 kPa to 16 kPa. As previously mentioned in the operating procedure, the TMP is the main measure of membrane fouling. Therefore, the stability of the TMP indicates a low level of membrane fouling.

Figure 6 also reflects 4 hour peak flux and 24 hour high flux tests, which were required by the CDPH as a part of the Title 22 certification testing protocol. The peaking tests are designed to ensure that in real applications, where the influent flow rate to a wastewater treatment plant varies throughout the day and week, the filtrate turbidity can still meet Title 22 requirements. The ten green circles represent the flux and corresponding TMP during five separate 4 hours peak flux tests at an instantaneous flux of 50.1 LMH (30 gfd). The average TMP at this flux was 18.6 kPa. This makes sense because more suction pressure is required to pull more water through the membrane. Immediately following the peak flux tests at 50.1 LMH, when the flux is reset to 33.1 LMH, the TMP returns to about 10 kPa, which indicates that the membrane did not suffer irreversible fouling during peak flux testing at 50.1 LMH. Because no irreversible fouling occurred at 50.1 LMH, Hydranautics and MRE staff decided to operate the final two peak flux tests at an increased instantaneous flux of 67.6 LMH (40 gfd). The average TMP at this flux was 30.3 kPa. When the flux was reset to 38.0 LMH, the TMP returned to 12-13 kPa, which was close to the average TMP at this flux. Therefore, 4 hour peak flux tests at 67.6 LMH did not result in irreversible fouling. The orange circles in Figure 6 reflect the first 24 hour high flux test. The flux was set to 41.4 LMH (24.5 gfd) and the corresponding average TMP was 13.8 kPa. After the first high flux test, the flux was reset to 33.1 LMH and the TMP returned to about 10 kPa. The second high flux test is indicated by the gray circles on Figure 6. Because of favorable results in the first high flux test, the second 24 hour high flux test was conducted at 45.4 LMH (26.9 gfd). The average TMP at this flux was 17.5 kPa. Before and after 24 hours of operation at 45.4 LMH, the flux was 38.0 LMH and the TMP was between 12-14 kPa, which once again indicated that no irreversible fouling occurred during the 24 hour high flux test. The stability of the TMP after all peak and high flux tests proved that HYDRAsub®/Sterapore SADF® MBR membranes are capable of handling the influent flow variations experienced at domestic wastewater treatment plants.

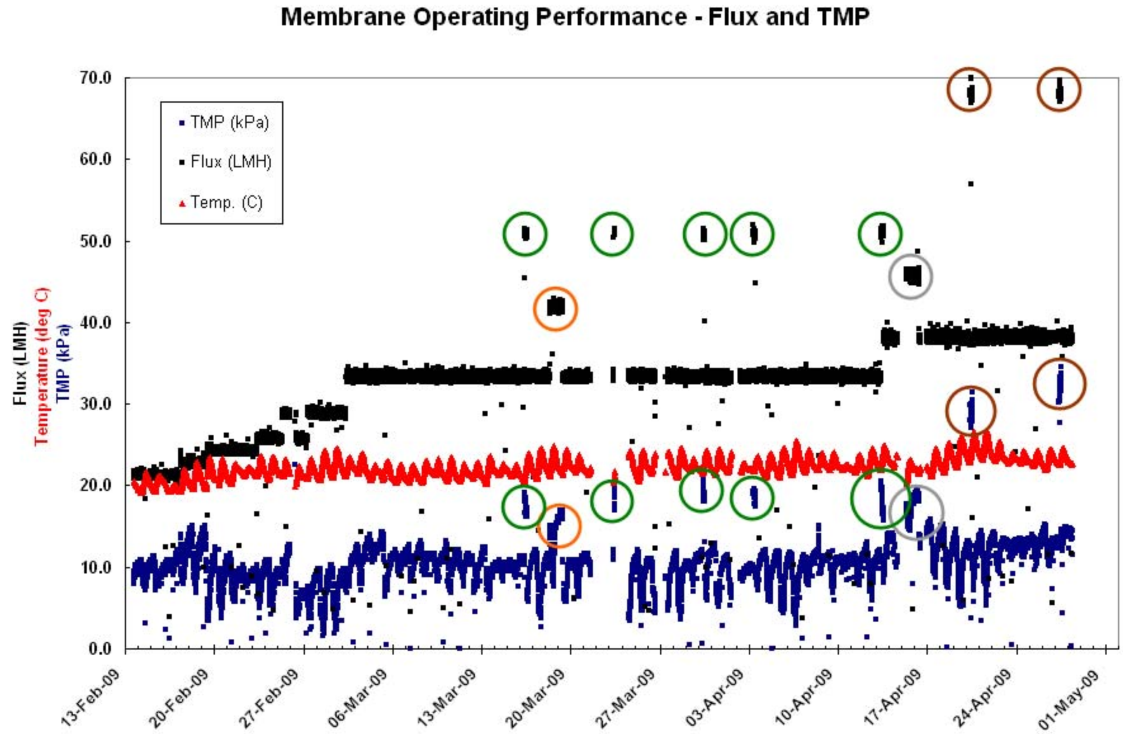

Figure 6: Flux, TMP, and Sludge Temperature

Filtrate Turbidity

Figure 7 shows the HYDRAsub®/Sterapore SADF® filtrate turbidity throughout the testing period. The black dotted line is at 0.2 NTU and the solid red line is at 0.5 NTU. As described above, Title 22 states that the turbidity of the filtered wastewater should not exceed 0.2 NTU more than 5 percent of the time within a 24-hour period and 0.5 NTU at any time. The average filtrate turbidity was 0.07 NTU, and the maximum was 0.410 NTU on April 14th. As the graph shows, the filtrate turbidity never exceeded 0.5 NTU, and only exceeded 0.2 NTU on five separate occasions. As was previously mentioned, the filtrate turbidity was recorded every 5 minutes for the test duration, with the exception of several data logging failures which occurred on March 21st, 23rd, 26th, and April 7th and 8th. The statistical analysis displayed in Figure 8 indicates that the filtrate turbidity that was below 0.2 NTU 99.9% of the time. Therefore, HYDRAsub®/Sterapore SADF® MBR membranes easily met the Title 22 requirement for membrane filtration.

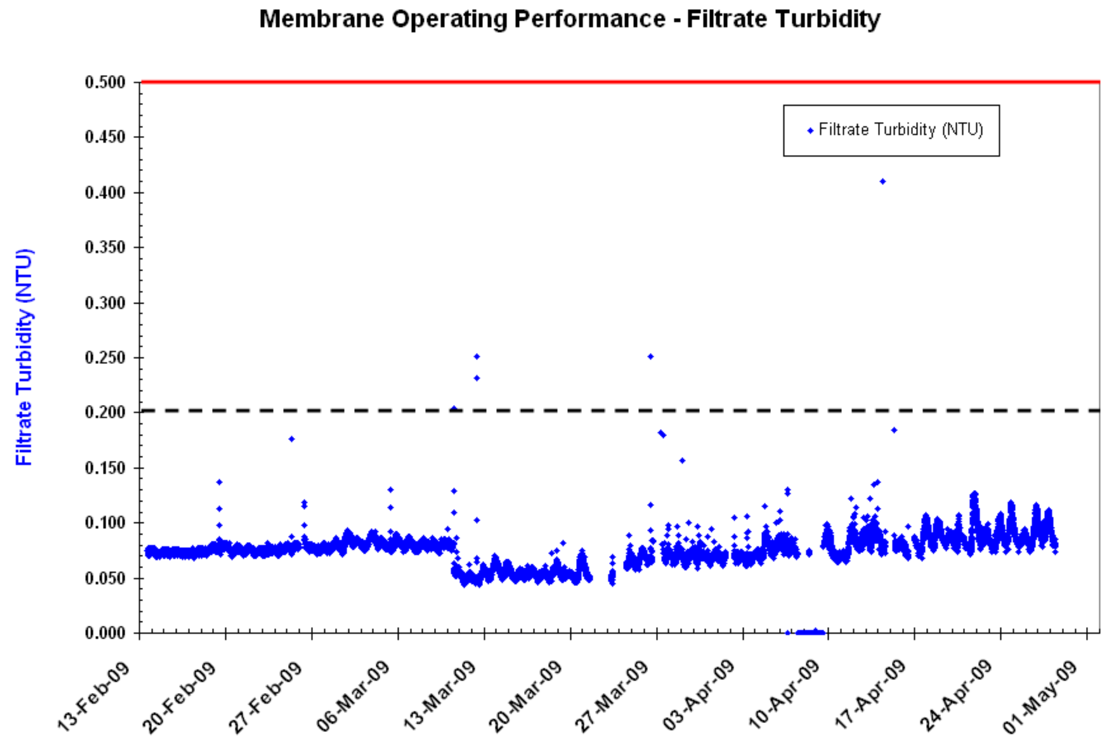

Figure 7: Filtrate Turbidity

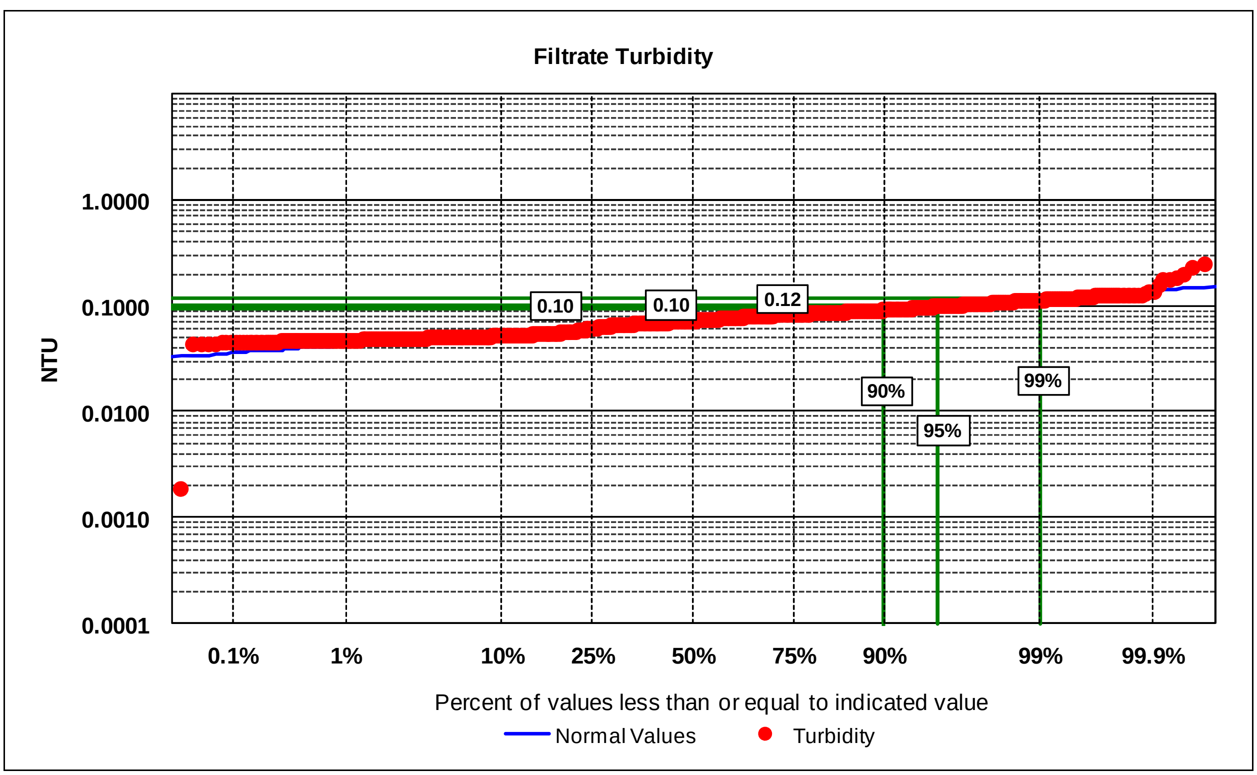

Figure 8: Probability Chart of Filtrate Turbidity from HYDRAsub® / Sterapore SADF® MBR

TSS Removal

The influent and effluent total suspended solids (TSS) concentrations displayed in Figure 9 were measured by Test America. The influent TSS varied between 42 mg/L and 100 mg/L. The effluent TSS was below the minimum detection limits (MDL) of the test in each analysis. The MDL was 10 mg/L.

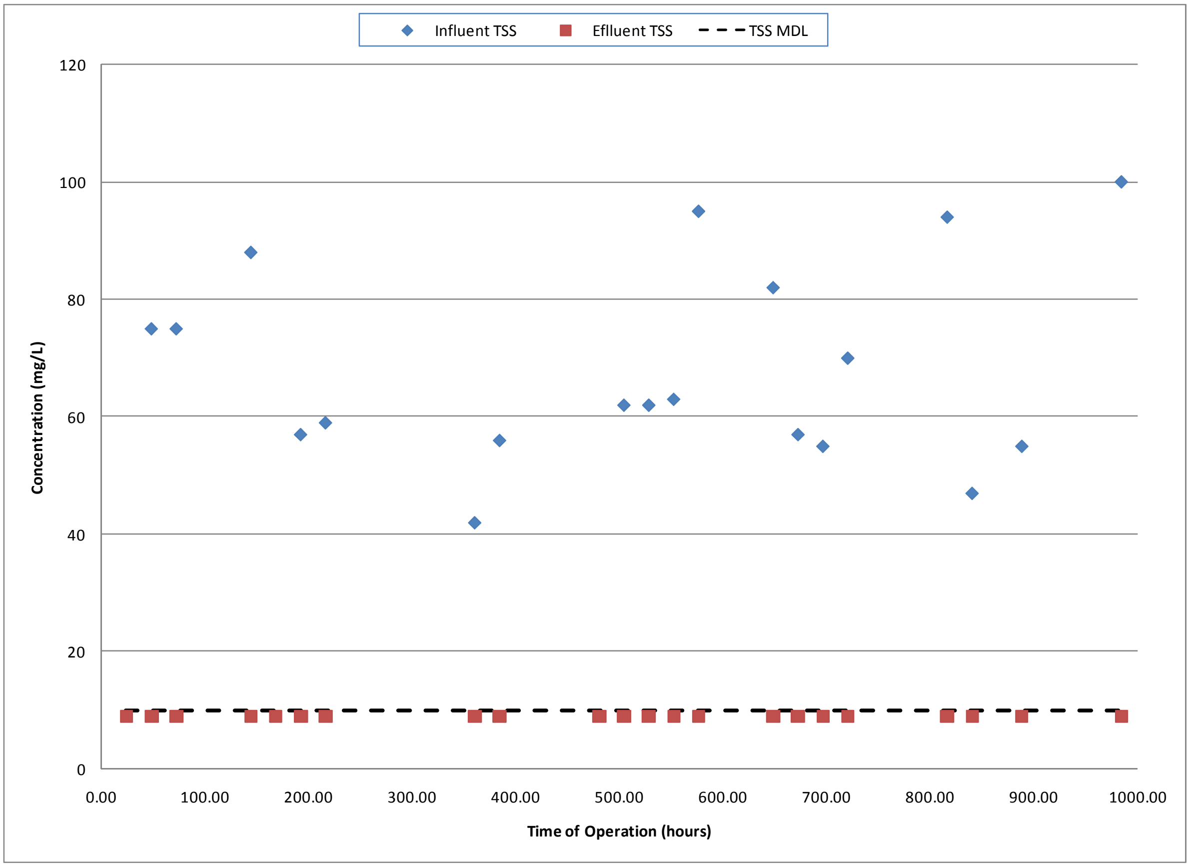

Figure 9: Influent and Effluent Total Suspended Solids Concentrations

Coliform Removal

Influent and effluent samples were taken on a weekly basis and analyzed for total and fecal coliform levels. The minimum detection limit (MDL) for fecal coliform was 2 MPN (Most Probable Number)/100 mL. In all effluent samples taken, the total and fecal coliform was below the MDL, indicating >6-log coliform removal capability. The results of the fecal coliform tests are shown in Table 4.

Table 4: Influent and Effluent Fecal Coliform Levels

Test Day	Fecal Coliform (MPN/100mL)		Concentration Change, Logarithmic
	Influent	Effluent	
3/16/2009	5.00E+06	<2	-6.39
3/23/2009	5.00E+06	<2	-6.39
3/30/2009	5.00E+06	<2	-6.39

4/06/2009	5.00E+06	<2	-6.39
4/13/2009	9.00E+06	<2	-6.65
4/15/2009	5.00E+06	<2	-6.39

Virus Removal

The results from the first virus removal test, performed at 33.1 LMH, are shown in Table 5.

Table 5: Anoxic tank and Filtrate MS2 Concentration at a filtrate flux of 33.1 LMH

Time After Beginning of Filtration (hours)	MS2 Concentration (PFU/100mL)		Concentration Change, Logarithmic
	Anoxic Tank	Filtrate	
1.67	1.10E+04	5	-3.34
3.83	1.20E+04	1	-4.08
5.67	1.20E+04	1	-4.08
7.67	1.00E+04	1	-4.00
24.08	6.20E+03	<1	-3.79

During the second virus removal test, the membranes operated at a flux of 50.1 LMH for four hours, and two samples were analyzed. The results are shown in Table 6.

Table 6: Anoxic tank and Filtrate MS2 Concentration at a filtrate flux 50.1 LMH

Time After Beginning of Filtration (hours)	MS2 Concentration (PFU/100mL)		Concentration Change, Logarithmic
	Anoxic Tank	Filtrate	
2.00	6.70E+03	<1	-3.83
4.00	5.60E+03	<1	-3.75

The final virus removal testing was performed at a flux of 45.4 LMH. The results are shown in Table 7.

Table 7: Anoxic tank and Filtrate MS2 Concentration at a filtrate flux 45.4 LMH

Time After Beginning of Filtration (hours)	MS2 Concentration (PFU/100mL)		Concentration Change, Logarithmic
	Anoxic Tank	Filtrate	
0	5.00E+03	18	-2.44
4.75	1.30E+04	2	-4.11
7.25	6.00E+03	<1	-3.77

It should be noted that the calculation for log removal depends on the virus concentration in the anoxic tank and the filtrate. Therefore, the higher the concentration in the anoxic tank the greater the log removal. At any rate, the HYDRAsub®/Sterapore SADF® MBR membranes average log removal of the MS2 bacteriophage was 3.72.

HYDRAsub®/Sterapore SADF® MBR Biological System Performance Results

Because of the solids barrier that the membranes provide in a MBR, the MLSS concentration in the system can be higher than that of a conventional activated sludge (CAS) system. As a result of the greater biomass and longer solids rentention times (SRT), the removal rate of BOD/COD and other biological nutrients, such as nitrogen, is higher in an MBR system than it is in a CAS system. Therefore, the effluent water quality of an MBR is not only better due to the membrane separation process, but also due to the enhanced biological process. Figure 10 shows the MLSS of the aeration tank and membrane tank throughout testing. An MLSS of 8000-12000 mg/L in the membrane tank is desired for optimal HYDRAsub®/Sterapore SADF® membrane performance.

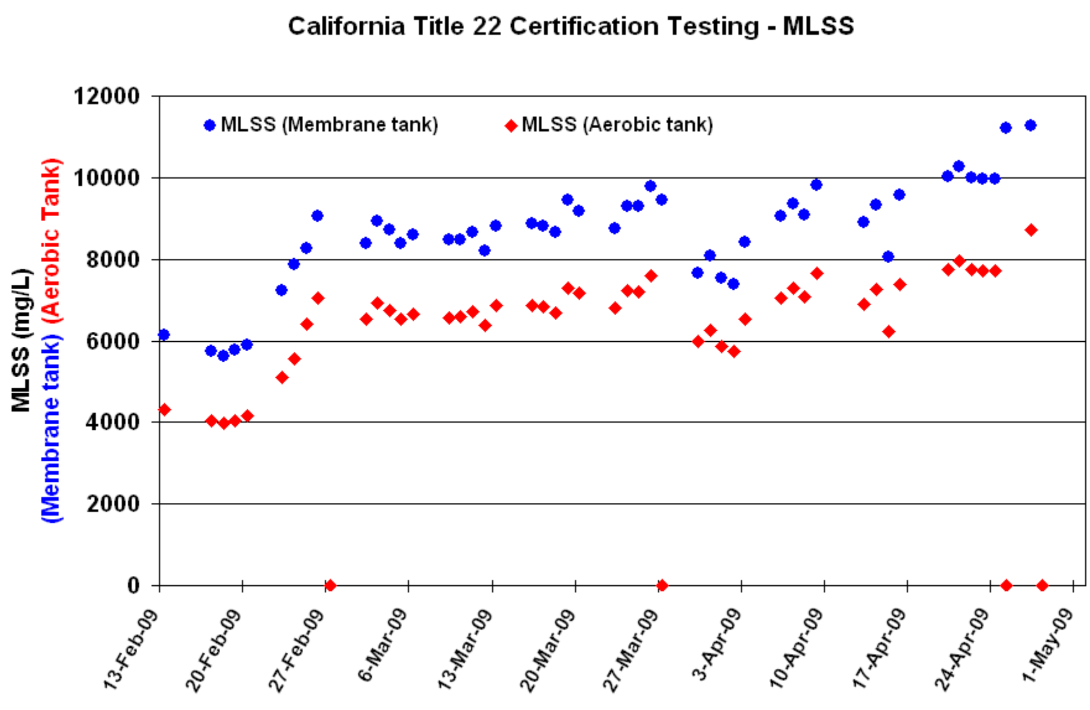

Figure 10: Aerobic Tank and Membrane Tank Mixed Liquor Suspended Solids

COD and BOD Removal

Figure 11 shows the influent and effluent chemical oxygen demand (COD) throughout testing. The influent COD averaged 306 mg/l, ranging from 270 mg/L to 445 mg/L. The dotted line on Figure 11 represents the minimum detection limit (MDL), which was 20 mg/L. Of the 22 effluent samples tested for COD, 11 were below the MDL. Assuming the effluent COD concentration of the samples below the MDL was equal to 20 mg/L, the average effluent COD was 21.42 mg/L, which corresponds to an average 93% removal.

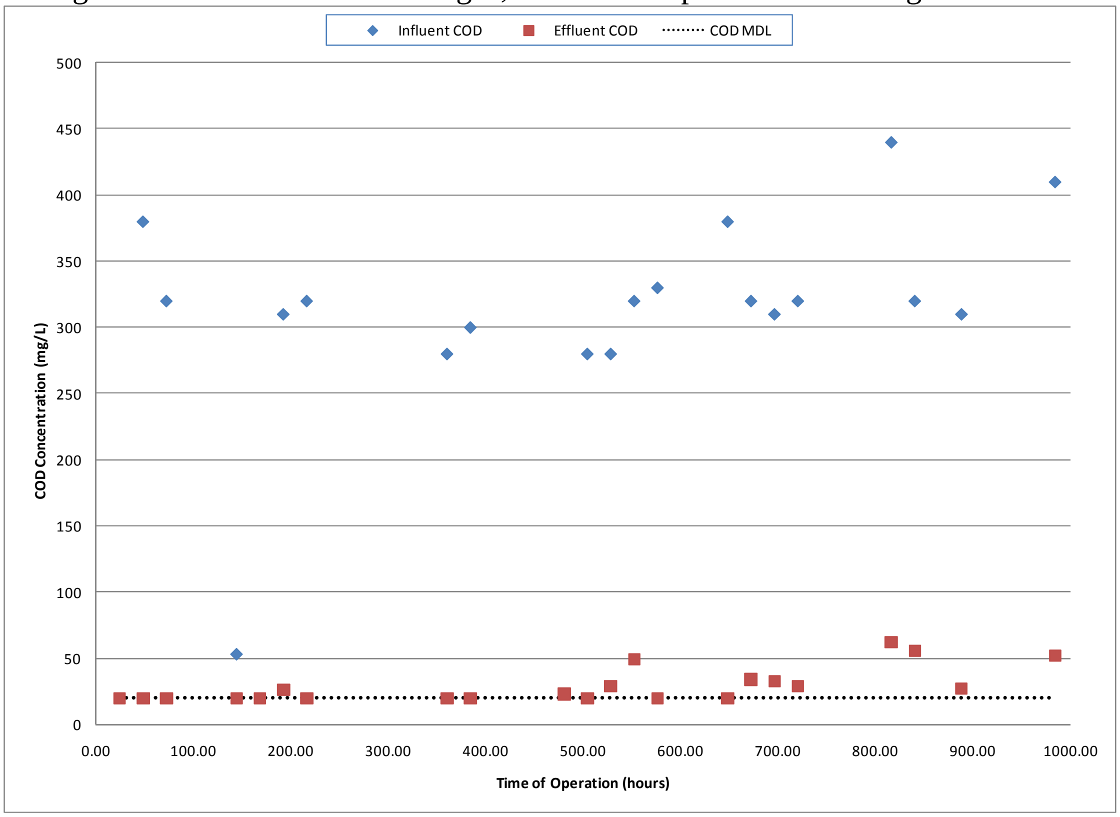

Figure 11: Influent and Effluent Chemical Oxygen Demand versus Time of Operation

Figure 12 shows the influent and effluent biochemical oxygen demand (BOD) during testing. The dotted black line represents the BOD MDL, which is 2 mg/L. The influent BOD concentration was between 120 mg/L and 190 mg/L, with an average of 149 mg/L. Of the 5 effluent samples analyzed for BOD, 2 of them were below the MDL. Assuming these samples had a BOD concentration of 2 mg/L, the average effluent BOD concentration was 2.98 mg/L, which corresponds to an average removal rate of 98%.

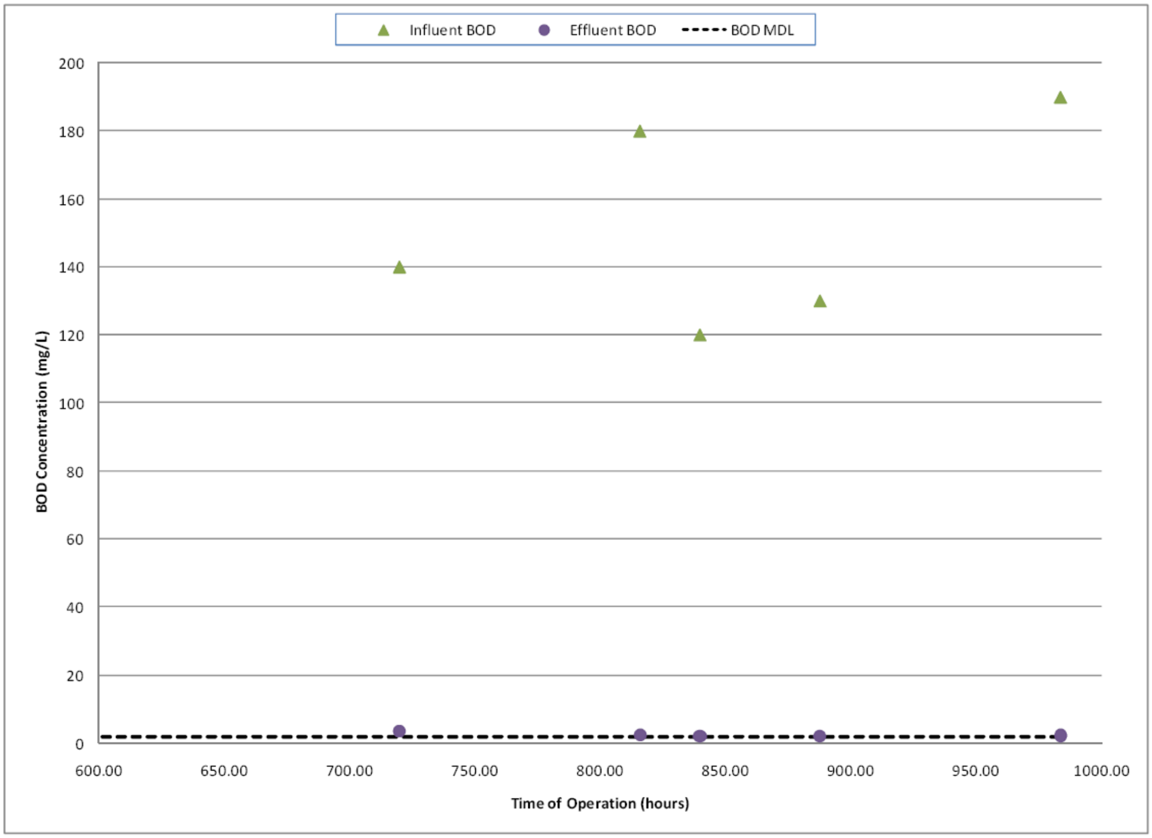

Figure 12: Influent and Effluent Biochemical Oxygen Demand versus Time of Operation

Total Kjeldahl Nitrogen (TKN) and Ammonia Removal

Influent and effluent Total Kjedahl Nitrogen (TKN) is shown in Figure 13. Influent TKN was between 55 and 130 mg/L, with an average of 70.35 mg/L. Effluent TKN was between 4.5 and 24 mg/L, with an average of 9.59 mg/L. This equates to an average TKN removal rate of 86%.

The influent and effluent ammonia concentrations are shown in Figure 14. Influent ammonia was between 37 and 100 mg/L, with an average of 68 mg/L. Effluent TKN was between 2.2 and 24 mg/L, with an average of 10.2 mg/L. This equates to an average TKN removal rate of 85%.

Effluent TKN and ammonia levels were higher than normal MBR effluent to due to insufficient DO in the aerobic tank, which was sometimes less than 1 mg/L.

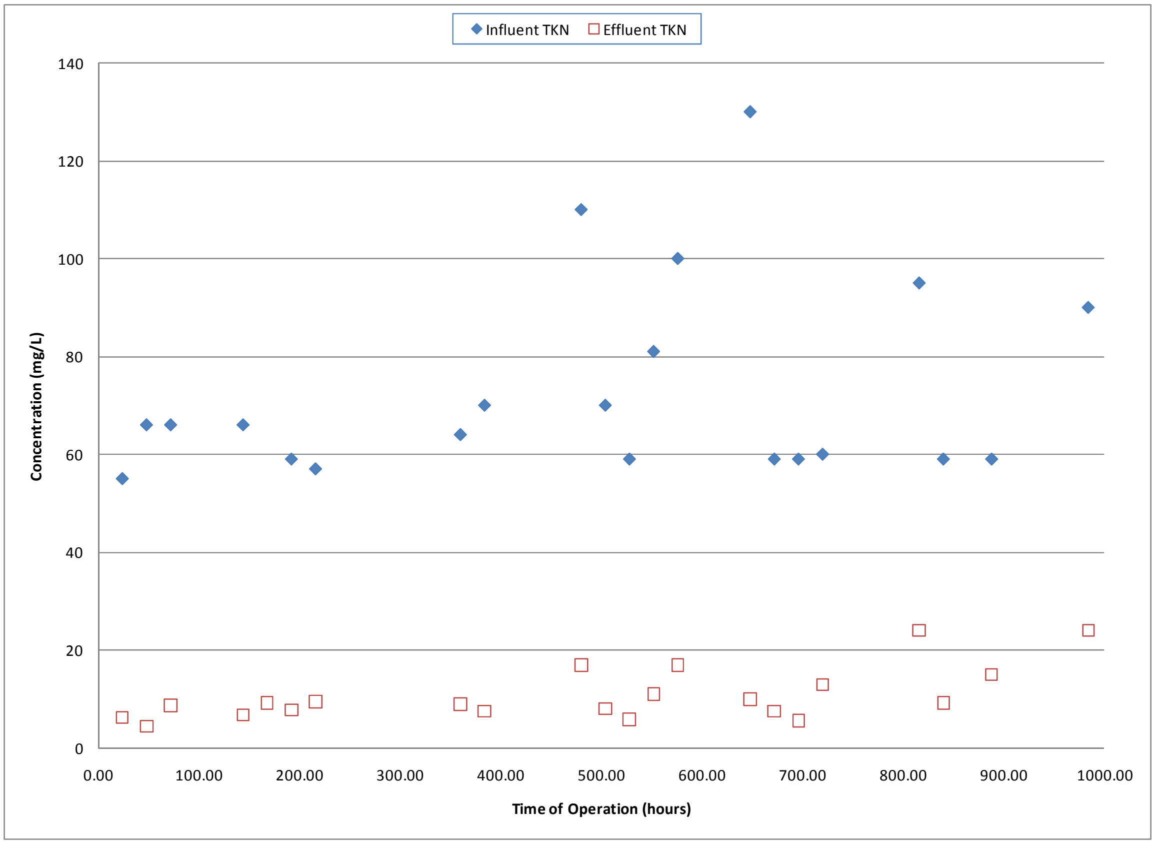

Figure 13: Influent and Effluent Total Kjeldahl Nitrogen versus Time of Operation

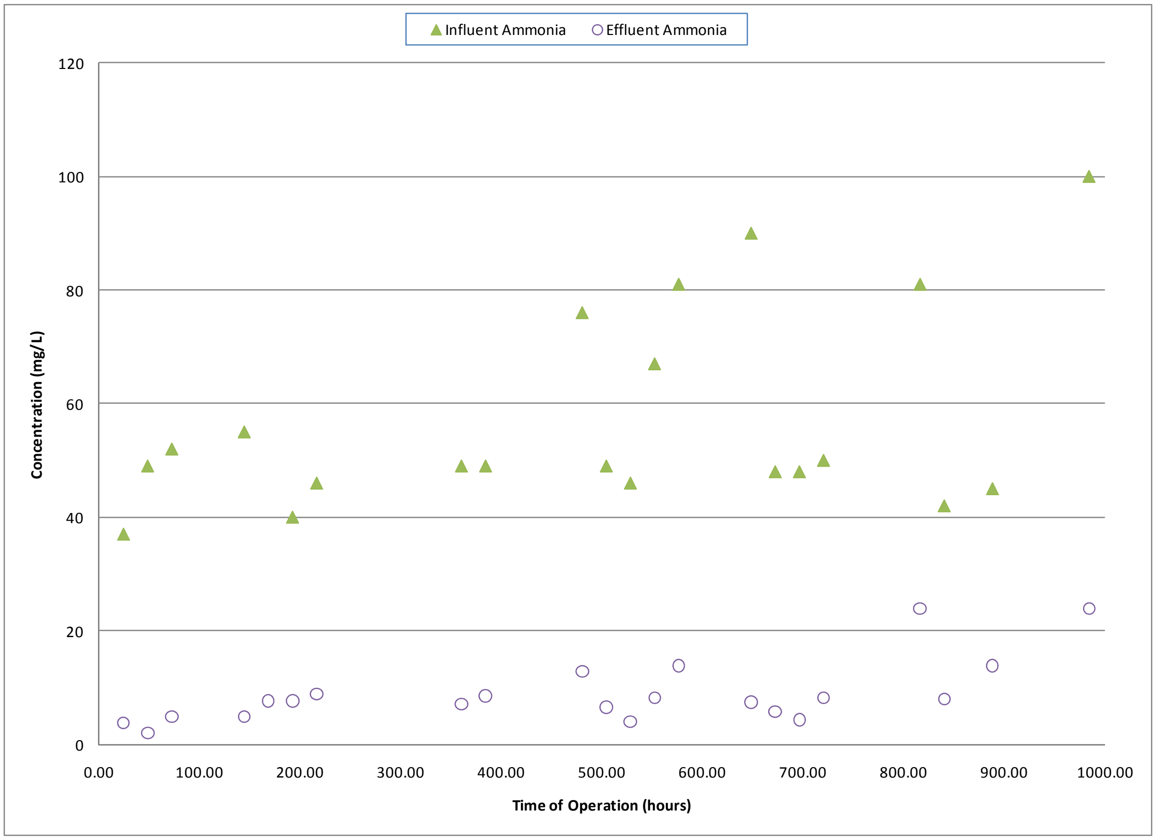

Figure 14: Influent and Effluent Ammonia versus Time of Operation

CONCLUSIONS

From the beginning of March 2009 to the end of April 2009, Hydranautics and MRE, with the help of HDR, conducted a CDPH approved pilot study which confirmed that HYDRAsub®/Sterapore SADF® MBR membranes are capable of consistently producing filtrate that meets the Title 22 requirements for domestic wastewater reuse. During the test period, the HYDRAsub®/Sterapore SADF® filtrate turbidity was less than 0.2 NTU 99.9% of the time and never exceeded 0.41 NTU, easily satisfying the Title 22 requirement for membrane filtered water.

Testing also showed HYDRAsub®/Sterapore SADF® MBR membranes capable of continuously operating at instantaneous fluxes of 33.1 LMH and 38.0 LMH while maintaining and average TMP of less than 13 kPa. Membrane performance during five separate four hour peak flux tests at an instantaneous flux of 50.1 LMH, two separate four hour peak flux tests at an instantaneous flux of 67.6 LMH, one 24 hour high flux test at an instantaneous flux of 41.4 LMH, and one 24 hour high flux test at an instantaneous flux of 45.4 LMH proved HYDRAsub®/Sterapore SADF® MBR membranes capable of handling fluctuations in the influent flow rate, which is to be expected in full scale applications. The TMP following the peak and high flux tests indicated that no irreversible fouling occurred.

In addition to low filtrate turbidity, virus removal testing at three different fluxes (33.1 LMH, 45.4 LMH, and 50.1 LMH) established an average of 3.72 log removal of the virus surrogate MS2 bacteriophage by HYDRAsub®/Sterapore SADF® MBR membranes.

Because of the HYDRAsub®/Sterapore SADF® MBR membranes, the MLSS in the biological treatment tanks was maintained between 6000-8000 mg/L. The high concentration of suspended solids in the system achieved 93% removal of COD, 98% removal of BOD, 86% removal of TKN, and 85% removal of ammonia.

After reviewing the data collected during this pilot study, which is summarized above, the California Department of Public Health accepted the use of HYDRAsub®/Sterapore SADF® MBR membranes as a filtration technology in compliance with the Title 22 Water Recycling Criteria in September of 2009.