

# **EVALUATION OF MOVING BED BIOFILM REACTOR TECHNOLOGY FOR ENHANCING NITROGEN REMOVAL IN A STABILIZATION POND TREATMENT PLANT**

Jeffery S. Weiss\*, Marcos Alvarez, Chi-Chung Tang, Robert W. Horvath, and James F. Stahl  
Sanitation Districts of Los Angeles County  
1955 Workman Mill Rd.  
Whittier, California 90601

## **ABSTRACT**

The Sanitation Districts of Los Angeles County (Sanitation Districts) operate the Palmdale Water Reclamation Plant (WRP) to provide wastewater treatment and disposal services for a city of 140,000. The Palmdale WRP is a secondary treatment system that uses oxidation ponds for BOD stabilization. Partial removal of nitrogen occurs within the facility, primarily as a result of assimilation by algae that subsequently settle to the pond bottom. Recent detections of nitrate nitrogen ( $\text{NO}_3\text{-N}$ ) in local groundwater have been attributed to the longstanding practice of land application of the nitrogen-rich plant effluent. In response to this groundwater impairment, the Sanitation Districts will upgrade the Palmdale WRP by 2009 with a tertiary treatment facility designed for biological nitrogen removal.

The Sanitation Districts also established a research program to assess methods to reduce nitrogen discharges from the Palmdale WRP in the interim. The evaluation of moving bed biofilm reactor (MBBR) technology described herein comprised part of that effort. The MBBR study was conducted in two phases. In Phase I, the MBBR was evaluated as an adjunct system to the existing ponds. The MBBR was operated to nitrify primary pond effluent for subsequent denitrification in the secondary pond. In Phase II, the MBBR was evaluated as a complete BOD and nitrogen removal system that could replace the oxidation ponds.

The Phase I study provided data to characterize the nitrification performance of the MBBR as a function of temperature, ammonia nitrogen ( $\text{NH}_3\text{-N}$ ) loading and dissolved oxygen concentration. Nitrification performance in MBBR was found to be more sensitive to dissolved oxygen levels than activated sludge systems. This characteristic was important for maintaining efficient nitrification performance during cold temperature operation.

In Phase II, the MBBR achieved an average nitrogen removal rate of 0.15 kg N/day per cubic meter of bioreactor volume (9.4 lb N/1000  $\text{ft}^3$ -day). This rate was greater than the rate observed at many conventional activated sludge systems that have implemented nitrogen removal. The solids yield from the pilot scale MBBR, 0.26 kg of waste biosolids per kg of COD removed, was lower than that observed at these full-scale plant. The Sanitation Districts concluded that MBBR is an effective technology that merits future consideration. MBBR appears capable of achieving treatment objectives in smaller biological reactors. Savings in clarifier design may also be possible. However, these advantages must be weighed against the costs for purchasing the MBBR media and higher energy costs for aeration.

## KEYWORDS

Moving bed biofilm reactor, pilot plant, nitrification, denitrification

## INTRODUCTION

The Sanitation Districts of Los Angeles County (Sanitation Districts) operate the Palmdale Water Reclamation Plant (WRP), a facility that provides wastewater treatment services for a city of 140,000 residents located in the high desert area north of Los Angeles. The plant, which began operation in 1953, currently treats an average flow of 9.2 million gallons per day (MGD). Its wastewater treatment operations are spread over two locations known as the 30<sup>th</sup> Street and the 40<sup>th</sup> Street sites. Raw wastewater is received at 30<sup>th</sup> Street where it is processed to remove grit and primary solids. Primary sludge is anaerobically digested and dewatered in drying beds.

The overflow from primary treatment is pumped to a system of stabilization ponds. Two ponds located at the 30<sup>th</sup> Street site provide BOD stabilization for less than 1 MGD of the primary effluent. The remaining flow is pumped to four larger ponds at the 40<sup>th</sup> Street location. The 40<sup>th</sup> Street ponds are arranged in two parallel trains each consisting of an aerated pond for BOD stabilization, and a secondary pond for settling. Each primary pond has twelve 25-hp floating aerators that operate during the evening hours. Algae, which naturally grow in oxidation ponds, supply oxygen during daylight hours through photosynthesis.

The location of the Palmdale WRP in a closed hydrological basin poses unique challenges for effluent management. The basin has no local body of surface water to receive the treated wastewater and to transport it out of the watershed. Effluent disposal includes a combination of land application and agricultural reuse. This long-term practice, however, has resulted in impacts on local groundwater quality. The final effluent can contain up to 25 mg N/L of ammonia nitrogen ( $\text{NH}_3\text{-N}$ ). As land-applied water percolates through the soil, the  $\text{NH}_3\text{-N}$  is microbiologically transformed to nitrate nitrogen ( $\text{NO}_3\text{-N}$ ).  $\text{NO}_3\text{-N}$  levels have been increasing at three groundwater monitoring wells downgradient of the effluent disposal area.

To ameliorate the water quality concerns posed by current operations, the Sanitation Districts committed to replacing the existing plant with a tertiary treatment facility capable of biological nitrogen removal. Start-up of the tertiary plant is scheduled for 2009. The Sanitation Districts also initiated a comprehensive research program to evaluate technologies that could be implemented economically to provide nitrogen reductions in the interim. As part of the testing program, the Sanitation Districts conducted a pilot plant study of an emerging wastewater technology, the moving bed biofilm reactor (MBBR). This paper presents the pilot study results and discusses their application with respect to the design of (1) a facility built as an interim measure to provide nitrification, and (2) a tertiary treatment facility for BOD and nitrogen removal based entirely upon MBBR technology.

## **Factors Limiting Nitrogen Removal in Oxidation Ponds**

Oxidation ponds provide a simple low-cost wastewater treatment solution when land is readily available and the discharge of a secondary effluent is acceptable. Nitrogen removal is observed to some degree in the ponds at Palmdale. The primary mechanism appears to be assimilation of  $\text{NH}_3\text{-N}$  nitrogen into algae that subsequently settle to the pond bottom. Nitrogen removal by the nitrification/denitrification (NDN) process does not occur to any measurable extent.

Physiological barriers to the establishment of significant nitrifier populations are thought to be the primary reason that NDN is not observed. Nitrifiers grow slowly and have the tendency to wash out of the oxidation pond. Establishment of a nitrifying population is further inhibited by the development of anoxic conditions in the ponds, particularly at night when the algae are not producing oxygen, and by low temperature. The large surface area of the Palmdale WRP oxidation ponds, over 600,000  $\text{m}^2$  (150 acres), facilitates rapid heat loss on cold winter days. Pond temperatures drop to below  $10^\circ\text{C}$  ( $50^\circ\text{F}$ ) for several weeks each winter.

Denitrifying bacteria, on the other hand, have higher growth rates, grow under both aerobic and anoxic conditions, and are less temperature sensitive. Thus, to enhance nitrogen removal at the Palmdale WRP, greater emphasis was placed on engineered solutions that would create environmental conditions more conducive to nitrifier growth, and that would incorporate mechanisms to retain nitrifiers within the system.

## **Moving Bed Biofilm Reactor**

The moving bed biofilm reactor (MBBR) concept was conceived in Norway during the 1980's, in response to agreements by eight European nations to reduce nitrogen loadings to the North Sea. Towards this end, the Norwegians focused on developing compact, small footprint, low maintenance attached growth system that minimized the operational and maintenance issues associated with trickling filters and rotating biological contactors. The first MBBR facility became operational in 1990 in Lardal, Norway. MBBR technology has since made significant penetration into the European market with an installed base of more than 300 MBBR systems. The number of installations in the United States at this time is small.

MBBR systems are based on reactors that are filled with plastic carriers to provide a surface that is colonized by bacteria that grow into a biofilm. The reactors can be operated under aerobic conditions for BOD removal and nitrification or under anoxic conditions for denitrification. During operation, the carriers are kept in constant circulation. In an aerobic reactor, circulation is induced through the action of air bubbles injected into the tank by a coarse bubble diffuser system. In an anoxic reactor, a submerged mixer is typically supplied. The carriers can occupy up to 70% of the reactor volume on a bulk volume basis. Experience has shown that mixing efficiency decreases at higher percentage fills.

Because MBBR is primarily an attached growth process, treatment capacity is a function of the specific surface area (SSA) of the reactor. The SSA for a reactor is calculated as the quotient of the total surface area on the carrier that is available for biofilm establishment and the reactor volume. The media has its own characteristic SSA. The media SSA reflects the amount of surface area available for biofilm development per unit volume of the media, on a bulk volume

basis. The reactor SSA equals the SSA of the media multiplied by the fraction of the total reactor volume that the media occupies (bulk volume basis). Table 1 lists the SSA for three different types of commercial MBBR media. The specific surface areas for rotating biological contactors and trickling filters are shown for comparison. The MBBR has a greater performance potential than these conventional fixed film type processes.

**Table 1 – Specific Surface Area for Attached Growth Media**

|                                      | <b>Specific Surface Area<br/>(m<sup>2</sup>/m<sup>3</sup>)</b> |
|--------------------------------------|----------------------------------------------------------------|
| <b>Trickling Filter Media</b>        |                                                                |
| Rock                                 | 45-60*                                                         |
| Plastic                              | 90-150*                                                        |
| <b>Rotating Biological Contactor</b> | 100-150*                                                       |
| <b>MBBR Media</b>                    |                                                                |
| Kaldnes K-1 Media                    | 500                                                            |
| Hydroxyl Media                       | 400                                                            |
| Kaldnes Flat Chip                    | 1200                                                           |

\* Data from Metcalf and Eddy (2003)

MBBR reactors use sieves to separate the circulating media from the wastewater being discharged. Retention of the media within the reactor encourages selection and enrichment for organisms that are best adapted to the nutrient conditions that prevail in that reactor at steady state.

## EXPERIMENTAL CONDITIONS

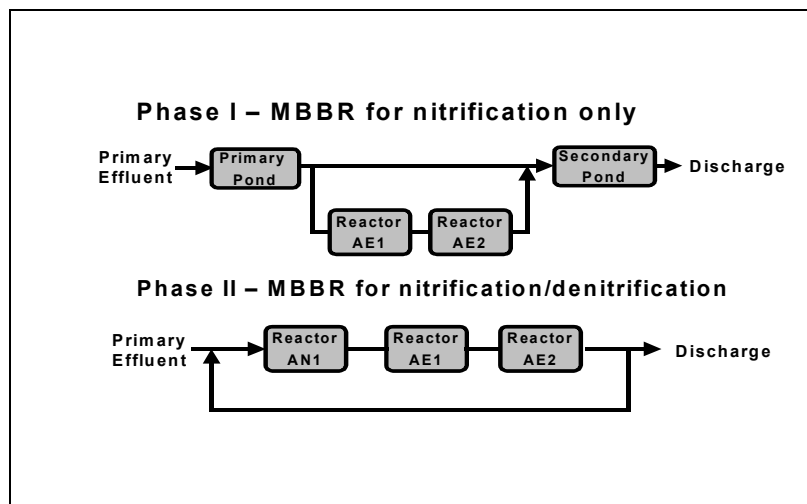
The Palmdale WRP MBBR evaluation was conducted in two phases. Figure 1 presents a flow schematic for each phase. In the Phase I study, the nitrification characteristics of the MBBR were assessed in a system consisting of two aerated reactors in series, each reactor having a volume of 0.61 m<sup>3</sup> (165 gallons). The reactors were designated as Reactor AE1 and Reactor AE2. Both reactors were filled 50% with Kaldnes K1 media on a bulk volume basis, providing a reactor SSA of 250 m<sup>2</sup>/m<sup>3</sup>. During the Phase I study, the influent flow was varied between 1.3 to 2.4 gallons per minute (gpm). The overall hydraulic residence time ranged from 2.3 to 4.4 hours.

The feed wastewater was drawn from the effluent end of a primary oxidation pond, a location where the wastewater is high in total Kjeldahl nitrogen and low in BOD. Using the primary oxidation pond to remove BOD ahead of the MBBR was expected to maximize the MBBR performance. At moderate to high BOD levels, heterotrophic bacteria can outcompete the slower growing nitrifiers for the finite space in the biofilm. Low BOD constrains the extent of heterotrophic growth thereby reducing the selective pressure against the nitrifiers.

In Phase II, the MBBR was configured as a complete biological treatment system for both BOD and nitrogen removal. Several modifications were made to the pilot plant before beginning this

phase. Most significantly, primary effluent replaced pond effluent as the feed wastewater. An anoxic reactor, Reactor AN1, was added at the front of the treatment train, which now consisted of three reactors in series. The anoxic reactor received the primary effluent feed as well as an internal recycle flow from the last reactor in the train. The volume of each reactor was increased to 0.73 m<sup>3</sup> (192 gallons). Kaldnes K-1 media was used as a carrier in all three reactors at a media fill percentage of 50%.

**Figure 1 – Flow Schematics for the Phase I and Phase II MBBR Pilot Plant Evaluation**



During Phase II, the primary effluent feed flow varied between 1.6 to 1.9 gpm corresponding to hydraulic residence times between 5.0 and 5.9 hours. The recycle flow ratio varied between 2:1 and 3:1.

## RESULTS

### Phase I Study

MBBR start-up occurred in early March 2004. Biofilm development required approximately four weeks. Operation and performance data for Phase I are presented in Tables 2, 3 and 4. This information represents averages values for six distinct periods of operation. Transitions between periods were normally marked by a change in either influent flow or airflow to the reactors. The last period of operation was distinguished from those preceding it by the low wastewater temperature. The results from this last period are discussed in greater detail in the section, Phase I Cold Temperature Study.

Limited BOD data was available for individual periods of operation and for this reason is not shown. The total BOD and soluble BOD for all MBBR influent samples averaged 150 mg/L and 20 mg/L, respectively. The total BOD data showed significant scatter. The total COD removal across the system was normally in the range of 10% to 20%. Much of the influent COD was in the form of algae. The influent total COD concentrations varied with the influent VSS levels that ranged from 88 to 214 mg/L. Effluent TKN concentrations, with the exception of the period

from May 9 to 22, were generally in the 10 to 20 mg N/L range. Much of this TKN was organic nitrogen fixed in algae cells that passed through the system essentially unchanged.

**Table 2 – MBBR Phase I Operating Conditions**

| Period of Operation | Flow Rate<br>(gpm) | Wastewater<br>Temperature (°C) | Dissolve Oxygen<br>(mg/L) |     | Air Flow<br>(scfm) |      |
|---------------------|--------------------|--------------------------------|---------------------------|-----|--------------------|------|
|                     |                    |                                | AE1                       | AE2 | AE1                | AE2  |
| April 5-May 1       | 1.54               | 17.8                           | 3.9                       | 4.2 | 4                  | 4    |
| May 2-8             | 1.55               | 21.7                           | 5.3                       | 7.5 | 8                  | 7    |
| May 9-22            | 2.28               | 19.6                           | 4.1                       | 4.4 | 10                 | 7    |
| May 23-29           | 2.31               | 19.5                           | 5.0                       | 5.2 | 17                 | 17   |
| June 7-22           | 1.48               | 23.3                           | 5.3                       | 6.0 | 10                 | 7    |
| July 19-22          | 1.35               | 12.2                           | 5.9                       | 9.0 | 6.6                | ---- |

**Table 3 – MBBR Phase I Influent and Effluent Water Quality**

| Period of Operation | Total COD (mg/L) |          | Soluble COD (mg/L) |          | TKN (mg N/L) |          | TSS (mg/L) |          | VSS (mg/L) |          |
|---------------------|------------------|----------|--------------------|----------|--------------|----------|------------|----------|------------|----------|
|                     | Influent         | Effluent | Influent           | Effluent | Influent     | Effluent | Influent   | Effluent | Influent   | Effluent |
| April 5-May 1       | 238              | 230      | 58                 | 63       | 32.8         | 21.2     | 98         | 97       | 88         | 89       |
| May 2-8             | 254              | 196      | 56                 | 44       | 35.5         | 15.4     | 139        | 103      | 118        | 91       |
| May 9-22            | 397              | 361      | 93                 | 123      | 57.5         | 54.4     | 313        | 140      | 224        | 127      |
| May 23-29           | 338              | 302      | 101                | 65       | 39.1         | 16.8     | 117        | 77       | 97         | 71       |
| June 7-22           | 268              | 202      | 82                 | 44       | 41.2         | 12.5     | 106        | 98       | 93         | 93       |
| July 19-22          | 386              | 196      | 61                 | 55       | —            | —        | 241        | 110      | 210        | 108      |

**Table 4 – MBBR Phase I Nitrification Performance**

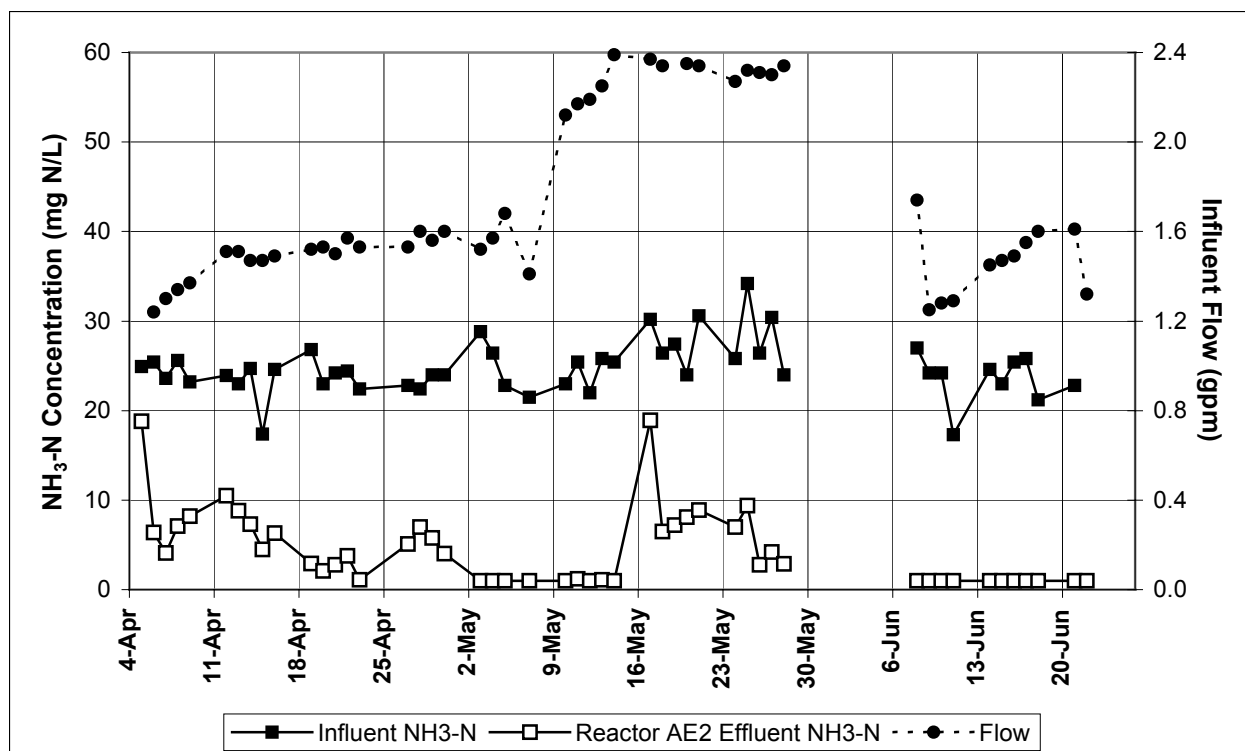
| Period of Operation | NH <sub>3</sub> -N (mg N/L) |      |      | NO <sub>2</sub> -N (mg N/L) |      |      | NO <sub>3</sub> -N (mg N/L) |      |      |
|---------------------|-----------------------------|------|------|-----------------------------|------|------|-----------------------------|------|------|
|                     | Influent                    | AE1* | AE2* | Influent                    | AE1* | AE2* | Influent                    | AE1* | AE2* |
| April 5-May 1       | 23.7                        | 15.6 | 6.1  | 0.06                        | 0.47 | 0.52 | <1.0                        | 9.5  | 20.0 |
| May 2-8             | 24.2                        | 5.9  | <1   | 0.07                        | 0.36 | 0.09 | <1.0                        | 21.1 | 24.7 |
| May 9-22            | 26.0                        | 14.3 | 7.4  | 0.06                        | 0.49 | 0.42 | <1.0                        | 11.9 | 22.3 |
| May 23-29           | 28.2                        | 16.8 | 5.2  | 0.10                        | 0.88 | 1.07 | <1.0                        | 12.1 | 25.6 |
| June 7-22           | 21.8                        | 3.9  | <1   | 0.29                        | 0.76 | 0.15 | <1.0                        | 24.0 | 30.9 |
| July 19-22          | 23                          | 6.3  | <3   | 0.16                        | 0.42 | 0.11 | <1.0                        | 19.5 | 24.7 |

\*Data represents effluent concentrations from Reactors AE1 and AE2

Figure 2 plots the influent and effluent NH<sub>3</sub>-N concentrations for the MBBR over a 12-week period (April 5 to June 22, 2004). Figure 2 also indicates the influent flow rate. Because the influent NH<sub>3</sub>-N concentration was relatively constant throughout Phase I, changes in the NH<sub>3</sub>-N loading rate paralleled changes in the influent flow.

Throughout April, the MBBR was operated at relatively steady conditions. The influent flow rate averaged 1.5 gpm and carried an average NH<sub>3</sub>-N concentration of 23.7 mg N/L. The airflow to each reactor was maintained at approximately 4 standard cubic feet per minute (scfm). The dissolved oxygen level (DO) in Reactor AE1 averaged 3.9 mg/L and fluctuated between 2.8 and 4.8 mg/L. In Reactor AE2, the DO averaged 4.2 mg/L and ranged from 3.0 to 5.9 mg/L. Daily NH<sub>3</sub>-N removals across the system were typically between 15 to 20 mg N/L. The effluent NH<sub>3</sub>-N concentration averaged 6.1 mg N/L.

**Figure 2 – Phase I MBBR Nitrification Performance**



Beginning the first week of May, the airflows to Reactor AE1 and Reactor AE2 were increased to 8 scfm and 7 scfm, respectively. In response to this change, the average DO levels in Reactors AE1 and AE2 increased to 5.3 mg/L and 7.5 mg/L, respectively. Following the increase in airflow, the NH<sub>3</sub>-N concentration in the Reactor AE2 effluent was consistently below the detection limit of 1 mg N/L.

To determine the maximum nitrification capability of the MBBR, the influent flow to the MBBR was increased on May 10. From May 10 through 21, the flow rate averaged 2.3 gpm. The airflow rate to Reactor AE1 was increased to 10 scfm to satisfy the additional oxygen demand posed by the higher NH<sub>3</sub>-N loading rate. From May 10 through 14, the effluent NH<sub>3</sub>-N concentrations remained near 1 mg N/L. However, the effluent NH<sub>3</sub>-N concentration increased the following week. This decline in nitrification performance occurred at the time of a pond turnover event. During pond turnover, organic materials that have accumulated on the pond bottom become suspended and can be drawn into the submersible pump used to supply pond water to the MBBR. Volatile suspended solids (VSS) levels in Reactor AE1, which averaged 197 mg/L during Phase I, averaged 413 mg/L between May 14 and 21. These solids were apparently biodegradable as the effluent from Reactor AE2 carried less VSS than the discharge from Reactor AE1. The oxygen demand associated with the solids degradation apparently caused DO reductions of 0.3 mg/L in Reactor AE1 and 1.0 mg/L in Reactor AE2. The airflow to both reactors was raised to 17 scfm on May 24 to compensate for the increased oxygen demand. DO levels increased into the range of 5.0-6.0 mg/L and overall NH<sub>3</sub>-N removals improved.

During the week of May 30 to June 5, the feed pump to the MBBR failed and the operation was interrupted. After correcting the pump problem, the influent flow rate was reduced and the airflow was set to 10 scfm for AE1 and 7 scfm for AE2. Effluent  $\text{NH}_3\text{-N}$  levels below 1 mg N/L were sustained from June 7 to the last day of operation on June 22. DO levels in Reactor AE1 varied between 4.5 to 6.9 mg/L during this period. The DO levels in Reactor AE2 fluctuated between 5.4 to 6.7 mg/L.

### **Phase I Cold Temperature Study**

As noted earlier, pond temperatures at Palmdale drop below 10°C each winter for periods lasting up to several weeks. Influent temperatures during the initial 12-week evaluation averaged 20°C. To establish that adequate nitrification could be sustained at winter temperatures, an evaluation of MBBR performance was conducted using a chiller to cool the oxidation pond effluent before feeding it to the MBBR.

The cold temperature study was conducted from July 19-22. Study results are included in Tables 2, 3 and 4. During this time, the MBBR feed temperature was maintained between 12.0 and 12.7°C. Near complete  $\text{NH}_3\text{-N}$  removal was achieved at an influent flow rate of 1.3 gpm. The airflow rate to Reactor AE1 was set at 8 scfm. Failure of a control valve prevented regulation of the airflow to Reactor AE2. During the test, the DO in Reactors AE1 and AE2 stabilized at approximately 5.9 mg/L and 9.0 mg/L, respectively. The high DO maintained in Reactor AE1 reflected the improved oxygen transfer efficiency that occurs at colder temperatures due to the higher saturation concentration of oxygen in water.

### **Phase II Study**

Start-up of the anoxic reactor AN1 occurred on August 10, 2004. A denitrifying biofilm developed in Reactor AN1 within two weeks. System performance was evaluated over a three-week period from August 23 to September 9. Performance data from Phase II are presented in Tables 5 and 6.

During Phase II, the mean influent flow was approximately 1.8 gpm and the internal recycle flow averaged 4.3 gpm. Influent temperature ranged from 27.4°C to 29.2°C. The MBBR effluent total COD and total BOD averaged 141 mg/L and 76 mg/L, respectively. The effluent, however, was not clarified prior to its discharge from the MBBR and typically contained 80 mg/L of VSS. The high VSS accounts for the high effluent total COD and BOD values

Figure 3 plots the influent TKN, effluent  $\text{NH}_3\text{-N}$ , effluent  $\text{NO}_3\text{-N}$  and effluent total inorganic nitrogen (TIN) for the Phase II study. TIN is calculated by summing the concentrations of  $\text{NH}_3\text{-N}$ ,  $\text{NO}_3\text{-N}$  and nitrite nitrogen ( $\text{NO}_2\text{-N}$ ). Influent TKN averaged 45.0 mg N/L and varied between 37.0 and 53.5 mg N/L. Some of the variability in the TKN concentration can be attributed to sampling procedures. Although all influent samples were morning grabs, the specific time of sampling differed from day to day. Data from other Sanitation Districts facilities indicate that influent TKN concentrations can change rapidly during the morning as the flow received at the plant increases. The range in the influent TKN data likely reflects differences in sample collection time.

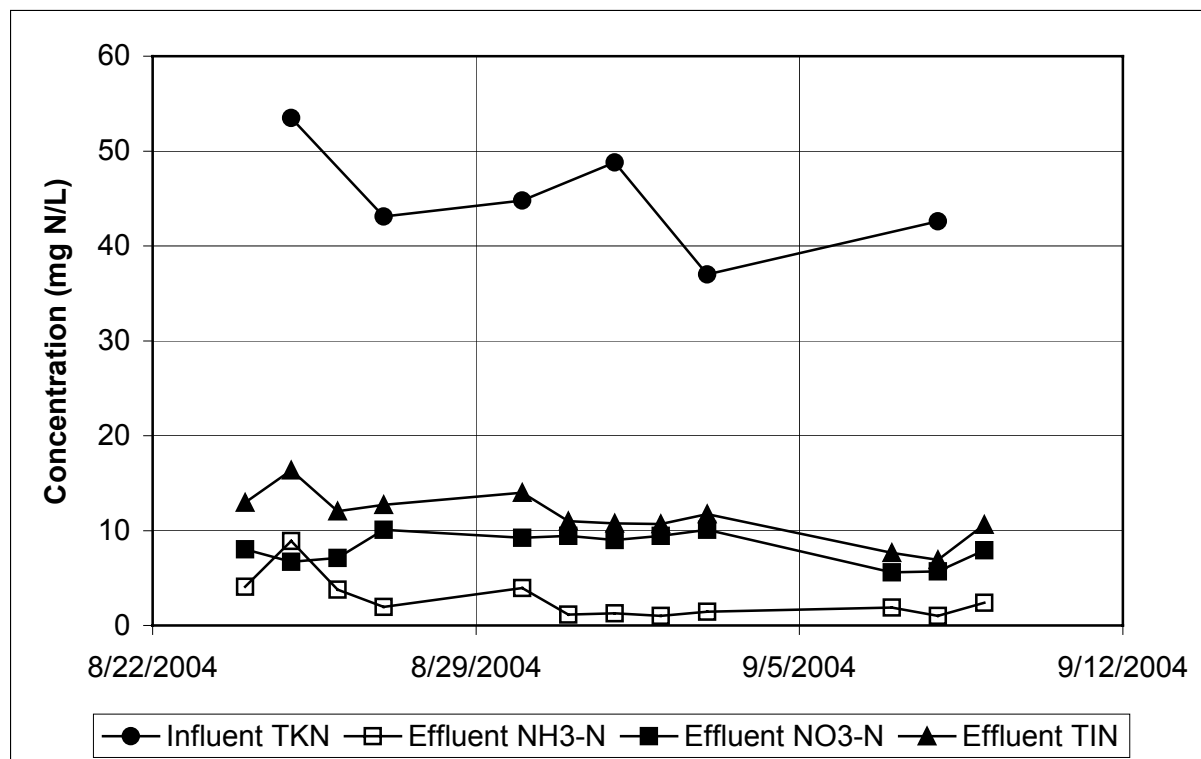
**Table 5 – MBBR Phase II: Overall Performance Data**

|                                  | Influent | Effluent |
|----------------------------------|----------|----------|
| Total COD (mg/L)                 | 372*     | 141      |
| Soluble COD (mg/L)               | 208      | 32       |
| Total BOD (mg/L)                 | 147      | 76       |
| Soluble BOD (mg/L)               | 84       | <6       |
| Total Suspended Solids (mg/L)    | ----     | 90       |
| Volatile Suspended Solids (mg/L) | ----     | 80       |
| Total Kjeldahl Nitrogen (mg N/L) | 45.0     | ----     |
| NH <sub>3</sub> -N (mg N/L)      | 33.6     | 3.1      |
| NO <sub>2</sub> -N (mg N/L)      | ----     | 0.5      |
| NO <sub>3</sub> -N (mg N/L)      | ----     | 8.2      |

\*Based upon analyses of total COD in 24-hour composite samples of Palmdale WRP primary effluent.

**Table 6 – MBBR Phase II: Nitrification/Denitrification Performance**

|                             | Reactor AN1 | Reactor AE1 | Reactor AE2 |
|-----------------------------|-------------|-------------|-------------|
| Dissolved Oxygen (mg/L)     | ----        | 3.8         | 4.4         |
| NH <sub>3</sub> -N (mg N/L) | 11.1        | 8.1         | 3.1         |
| NO <sub>2</sub> -N (mg N/L) | 0.3         | 0.4         | 0.5         |
| NO <sub>3</sub> -N (mg N/L) | 1.5         | 2.9         | 8.2         |

**Figure 3 – MBBR Phase II Nitrogen Removal Performance**

The total inorganic nitrogen in the MBBR effluent varied between 6.9 and 16.4 mg N/L. The extent of nitrogen removal, as calculated from the difference between the influent TKN and the effluent TIN, ranged from 68% to 84%, and averaged 75%.

Effluent TIN tended to decrease as Phase II progressed. The decrease paralleled a decrease in the effluent  $\text{NH}_3\text{-N}$  from the MBBR system. Effluent  $\text{NH}_3\text{-N}$  was particularly high during the first week of data collection. During that period, nitrification in Reactor AE1 was inefficient with only 1.0 to 1.7 mg N/L of  $\text{NH}_3\text{-N}$  being converted. This inefficiency had a cascade effect. Reactor AE2 became overloaded with  $\text{NH}_3\text{-N}$  and was unable to complete the nitrification process. Less  $\text{NO}_3\text{-N}$  was recycled back to Reactor AN1 to complete the nitrogen removal process.

Figure 4 illustrates the changes in the nitrification dynamics in the Reactors AE1 and AE2 more clearly. The data in Figure 4 are presented on the basis of mass removal rate per unit surface area. Normalization to surface area removes the effect that fluctuations in influent and internal recycle flow rates have on concentration. Initially, Reactor AE1 nitrified approximately 200 mg  $\text{N/m}^2\text{-day}$  of  $\text{NH}_3\text{-N}$ . This rate later accelerated to between 600 to 1000 mg  $\text{N/m}^2\text{-day}$ . As performance in Reactor AE1 increased, the removal rates in Reactor AE2 declined. This decline arose from the improved performance in Reactor AE1, which reduced the loading to Reactor AE2 well below its potential capacity.

**Figure 4 – MBBR Phase II Nitrification Rates in Reactors AE1 and AE2**

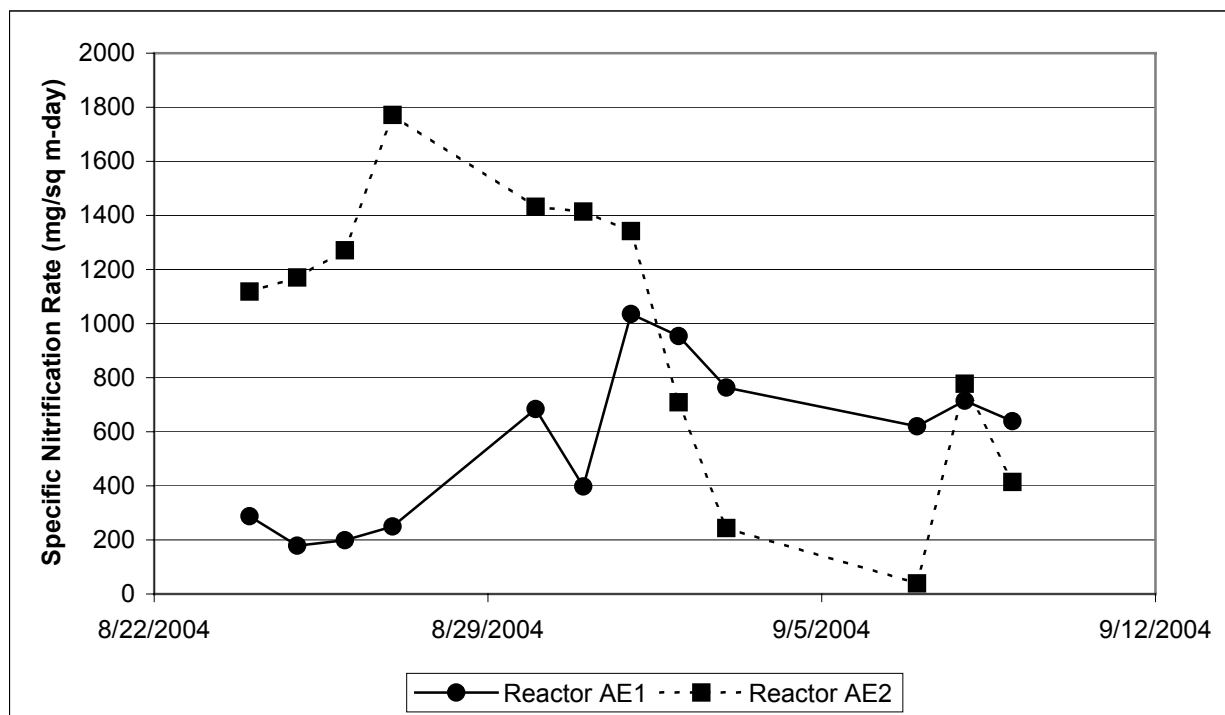
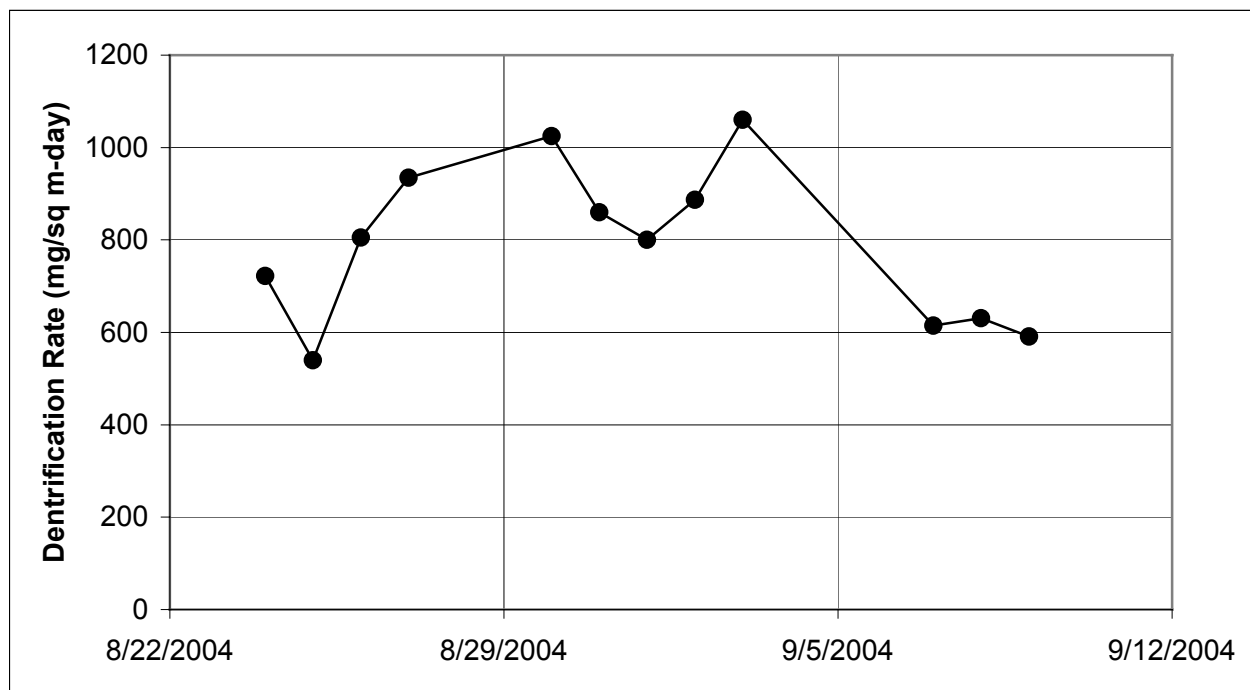


Figure 5 plots the denitrification rate calculated for Reactor AN1. The denitrification rates were determined by calculating the mass per day of  $\text{NO}_3\text{-N}$  returned to Reactor AN1 by the internal recycle stream, subtracting out the unreacted  $\text{NO}_3\text{-N}$  in the Reactor AN1 effluent, and dividing by the surface area of the plastic media carriers. The denitrification rate varied between 600 to 1,050 mg  $\text{N/m}^2\text{-day}$  and averaged 790 mg  $\text{N/m}^2\text{-day}$ . Lower rates were measured at the beginning and at the end of study. The low rates at the beginning are a consequence of the low nitrification performance in Reactor AE1, as discussed above. The higher denitrification rates measured during the middle of Phase II suggests that Reactor AN1 was underloaded with  $\text{NO}_3\text{-N}$ .

at the beginning of Phase II. The decline in the denitrification rate at the end of Phase II coincided with the lowering of the influent flow rate from 1.9 gpm to 1.6 gpm. The lower denitrification rate was due more to the lower overall nitrogen loading rate to the system than to a loss of denitrification performance.

**Figure 5 – MBBR Phase II Denitrification Rates**



The average TKN loading to the pilot plant during Phase II was approximately 0.44 kg/day (0.97 lb/day). The system discharged approximately 0.11 kg/day (0.25 lb/day) of TIN. The nitrogen removal rate for the MBBR on a total system volume basis was 0.15 kg N/m<sup>3</sup>-day (9.4 lb/1000 ft<sup>3</sup>-day).

The MBBR was operated without a clarifier or sludge recycle. The generation of waste solids was calculated from the average TSS concentration of 90 mg/L in the effluent from Reactor AE2. The COD reduction across the MBBR averaged 340 mg/L. The system discharged approximately 0.26 kg of solids per kg of COD removed.

## DISCUSSION

The data from Phase I and Phase II were analyzed to develop kinetic relationships that could be applied to sizing reactors for implementation of MBBR as (1) an interim nitrification treatment that relies upon the existing oxidation ponds for denitrification, and (2) as a system that provides treatment for both nitrogen and BOD removal.

## Analysis of Phase I data

Nitrification rates are influenced by the concentration of both  $\text{NH}_3\text{-N}$  and dissolved oxygen. In a nitrifying MBBR, one of these substrates tends to rate limiting. Nitrification rates will be sensitive to the changes in concentration of this limiting substrate and minimally affected by concentration changes in the non-limiting reactant. Odegaard et al. (1994) indicate that in MBBRs, oxygen limited conditions prevail when the bulk liquid  $\text{NH}_3\text{-N}$  concentration is greater than 3 mg N/L.  $\text{NH}_3\text{-N}$  limits the nitrification rate below this threshold.

When a low  $\text{NH}_3\text{-N}$  effluent concentration must be achieved, the MBBR should be staged to minimize the total system volume required. In a staged system, nitrification will be oxygen limited in the lead reactor and  $\text{NH}_3\text{-N}$  limited in the last reactor. Staging takes maximum advantage of the difference between MBBR reaction kinetics under each regime. Development of guidelines for sizing oxygen limited and  $\text{NH}_3\text{-N}$  limited reactors are discussed below.

Rittman and McCarty (2001) provide a detailed mathematical analysis of the kinetics of biofilm based-treatment systems. Based upon their discussion, the nitrification rate was assumed to respond linearly to changes in the concentration of the limiting substrate over the range of conditions tested in Phase I. Data collected under oxygen-limited conditions were thus expected to fit an equation in the following form:

$$r_N = k \cdot (DO - b) \cdot \theta^{(T-20)}$$

where,

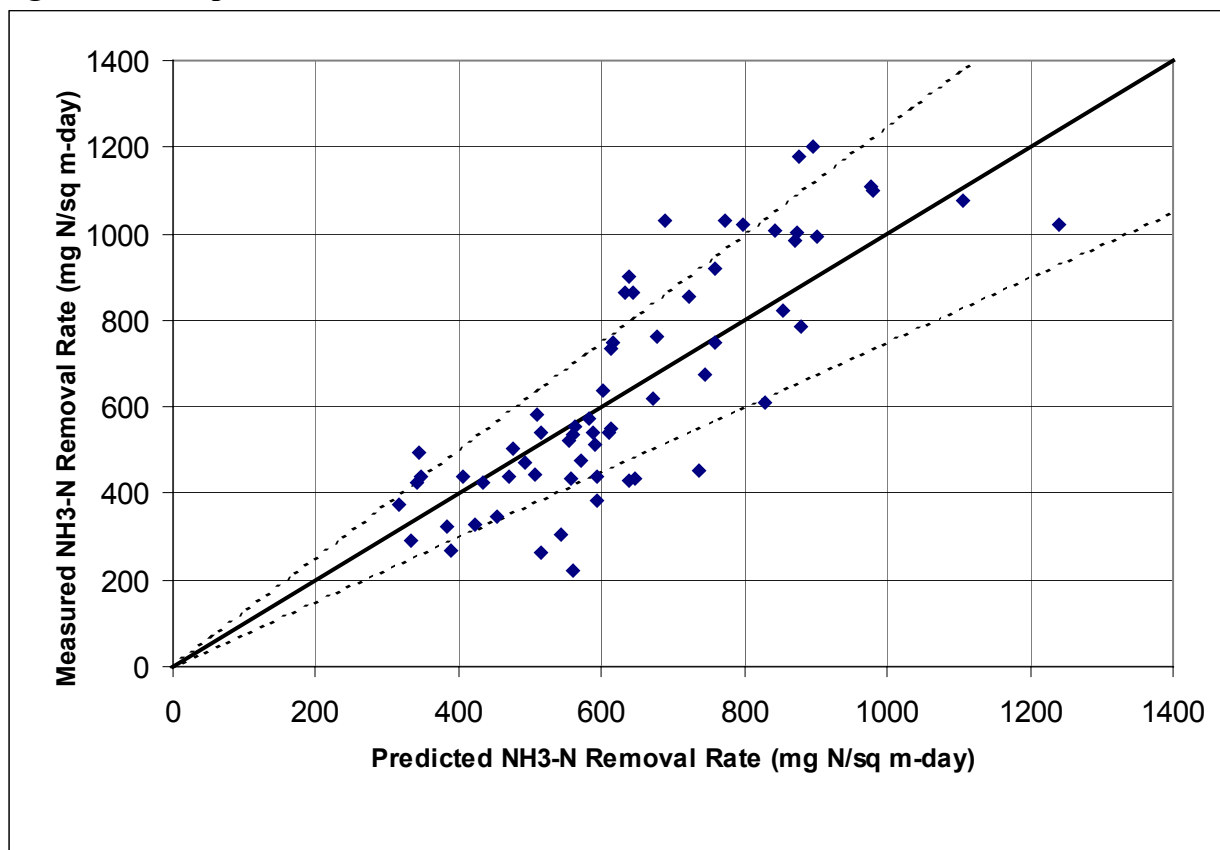
- $r_N$  = nitrification rate per unit surface area ( $\text{mg NH}_3\text{-N/m}^2\text{-day}$ )
- $k$  = first order rate constant ( $\text{L/m}^2\text{-day}$ )
- $DO$  = dissolved oxygen concentration in the bulk liquid ( $\text{mg/L}$ )
- $b$  = dissolved oxygen adjustment constant ( $\text{mg/L}$ )
- $\theta$  = Arrhenius type temperature correction factor
- $T$  = wastewater temperature ( $^{\circ}\text{C}$ )

A DO adjustment constant is included in the equation because the Rittman and McCarty (2002) treatment indicates that the linear response to the limiting substrate does not extend all the way to zero concentration. The Arrhenius factor adjusts for temperature effects.

The proposed rate expression contains three constants,  $k$ ,  $b$  and  $\theta$ . The values of these constants were estimated using a non-linear least squares analysis procedure. The nitrification rate,  $r_N$ , was the independent variable, and  $DO$  and  $T$  were dependent variables. The regression analysis was restricted to data points corresponding to an oxygen-limited condition. For each data point, a value for  $r_N$  was calculated by multiplying the flow rate to the reactor by the change in the  $\text{NH}_3\text{-N}$  concentration across the reactor. This result was then divided surface area on the media. The regression yielded least squares estimates of  $k=213.6 \text{ L/m}^2\text{-day}$ ,  $b=1.15 \text{ mg/L}$  and  $\theta=1.047$ . The square of the correlation coefficient was found to be 0.65.

Figure 6 compares measured nitrification rates under oxygen-limited conditions against the rates predicted by the regression equation. Points that fall on the solid diagonal line represent a perfect match between measured and predicted rates. Points within the dotted diagonal lines represent measured values that are within 25% of the predicted. The regression relationship shows a reasonable fit to the field data.

**Figure 6 – Comparison of Measures and Predicted Nitrification Rates**



The precision of the data generated under  $\text{NH}_3\text{-N}$  limited conditions did not permit an analysis similar to that described above. Reactors operating in the  $\text{NH}_3\text{-N}$  regime tended to have  $\text{NH}_3\text{-N}$  concentrations that were less than the 1 mg N/L detection limit. Without more definite  $\text{NH}_3\text{-N}$  concentration information, the regression procedure described above could not be applied.

As an alternative, loading rates were calculated for each data point collected under  $\text{NH}_3\text{-N}$  limited operation. Each loading rate was paired with the effluent  $\text{NH}_3\text{-N}$  concentration that resulted under that given load. A loading rate less than 650  $\text{mg N/m}^2\text{-day}$  always produced an effluent containing less than 1 mg N/L of  $\text{NH}_3\text{-N}$ . On six occasions, a reactor was loaded with between 650 and 880  $\text{mg N/m}^2\text{-day}$ . On four of those six days, the system also produced an effluent of less than 1 mg N/L  $\text{NH}_3\text{-N}$ . On the other two days, effluents of 2.1 mg/L and 2.8 mg/L were produced for loadings of 700 and 725  $\text{mg N/m}^2\text{-day}$ . The data indicate that limiting the  $\text{NH}_3\text{-N}$  loading rate to 650  $\text{mg N/m}^2\text{-day}$  will reliably produce an effluent containing less than 1 mg N/L. This finding applies for a temperature of 18°C and must be adjusted for the actual design operating temperature.

## **Analysis of Phase I Cold Temperature Study Data**

Nitrification rates for Reactor AE1 were calculated for the period of July 19-23 when the wastewater feed temperature averaged 12.2°C (54°F). These rates were compared to the rates calculated for the period of May 1 through June 22. Median feed temperature during the earlier period was 21°C (70°F). Reactor AE1 nitrified an average of 840 mg N/m<sup>2</sup>-day when receiving the chilled feed versus 970 mg N/m<sup>2</sup>-day when the pond water was fed at ambient temperature. The performance difference between chilled and unchilled feed was approximately 15%.

## **Analysis of Phase II data**

For a nitrification/denitrification system to operate effectively, the total NO<sub>2</sub>-N plus NO<sub>3</sub>-N concentration in the discharge from the anoxic reactor should be near zero. During Phase II, Reactor AN1 produced an effluent containing more than 2 mg N/L NO<sub>2</sub>-N plus NO<sub>3</sub>-N for five of twelve sampling events. High NO<sub>2</sub>-N plus NO<sub>3</sub>-N levels indicate that either the influent BOD does not supply sufficient amounts of electron donors to drive denitrification to completion (stoichiometric limitation) or that the anoxic reactor is undersized (kinetic limitation). Stoichiometric limitation may occur when the ratio of ultimate BOD to TKN in the influent is less than 5. The ratio for the Palmdale WRP primary effluent during the Phase II period was approximately 8. Kinetic limitation is a more plausible explanation for the days on which the NO<sub>2</sub>-N plus NO<sub>3</sub>-N concentrations exceeded 2 mg N/L. On those days, the loading rate of NO<sub>2</sub>-N plus NO<sub>3</sub>-N to Reactor AN1 ranged from 1,110 to 1,600 mg N/m<sup>2</sup>-day. When the effluent from Reactor AN1 contained less than 1 mg N/L NO<sub>2</sub>-N plus NO<sub>3</sub>-N, the loading rate ranged from 760 to 1,180 mg N/m<sup>2</sup>-day and averaged 930 mg N/m<sup>2</sup>-day. The average operating temperature on these days was 27.5°C. To achieve acceptable denitrification, the NO<sub>3</sub>-N plus NO<sub>2</sub>-N load to an anoxic MBBR should be limited to 930 mg N/m<sup>2</sup>-day at a temperature of 27.5°C. This loading rate must be adjusted to the actual design temperature.

## **Nitrogen Removal**

Nitrogen removal rates during Phase II operation were calculated and compared to removal rates achieved during 2004 at seven Sanitation Districts' water reclamation plants that practice nitrogen removal. Removal rates were calculated from the difference between the mass load of TKN in the primary effluent and the mass load of TIN in the plant discharge. This difference was divided by the total bioreactor volume of the facility. The results of this analysis are presented in Table 7.

The nitrogen removal rate in the Phase II MBBR was 50% greater than the average for the seven operating WRPs. Operating conditions may explain part of observed difference. For example, during Phase II, the MBBR received a relatively warm influent feed. Some of the full-scale plants are operating below their design loading capacity and thus may not be fully stressed. TKN to BOD ratios, which may significantly affect performance, vary from facility to facility. Nonetheless, the difference in performance was substantial. MBBR is clearly an efficient treatment technology that can achieve specific nitrogen removal objectives in a smaller total bioreactor volume than comparable activated sludge plants.

**Table 7 – Nitrogen Removal Rates**

|                                                           | Nitrogen Removal Rate<br>(kg N/m <sup>3</sup> -day) |            |
|-----------------------------------------------------------|-----------------------------------------------------|------------|
|                                                           | Average                                             | Range      |
| MBBR                                                      | 0.15                                                | 0.13-0.16  |
| Existing Sanitation Districts<br>Water Reclamation Plants | 0.10                                                | 0.074-0.15 |

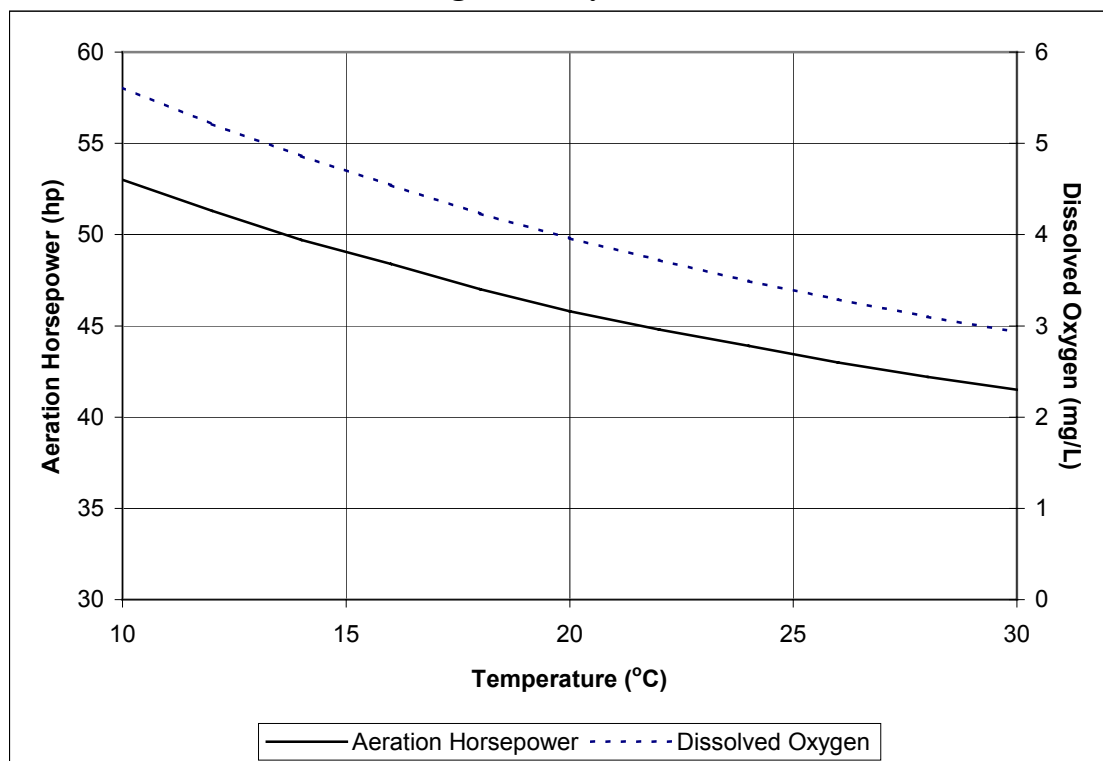
### **Aeration Considerations**

The Phase I regression equation suggests that nitrification in an oxygen limited MBBR requires a minimum DO concentration of 1.15 mg/L. This finding is consistent with data presented by Hem et al. (1994) and Odegaard et al. (1994). Practical nitrification rates in MBBR reactors can only be achieved at DO concentrations above the 2.0 mg/L DO target commonly used in nitrifying activated sludge systems.

Management of DO levels is more critical in optimizing the design and operation of MBBRs for nitrification than it is for comparable activated sludge plants. The Phase I data suggest that at a given temperature, a DO increase from 2 mg/L to 6 mg/L accelerates nitrification by a factor of 5.7. A similar change in a suspended growth system produces only a 28% rate increase. In both types of systems, nitrification will slow as temperature declines. Increasing the DO concentration during cold temperature operation can compensate for the slower nitrification rate, but the compensatory effect is far greater for the MBBR. As demonstrated in the Phase I cold temperature study, nitrification rates at low temperature can be brought to within 15% of those achieved with warmer influent feeds.

The DO increase for cold operation will increase power consumption for aeration. But the solution behavior of oxygen partially mitigates this penalty. As temperature decreases, oxygen becomes more soluble in the wastewater. This increases the driving force for the transfer of gaseous oxygen from the aeration bubble into solution. As a result, oxygen transfer efficiency increases. Figure 7 plots, as a function of temperature, the power required to transfer 1000 kg of oxygen per day to maintain a DO that supports a nitrification rate of 600 mg N/m<sup>2</sup>-day. Power requirements increase by approximately 25% over this range.

**Figure 7 – Aeration Horsepower and Dissolved Oxygen Concentration Required to Sustain Nitrification at the Rate of 600 mg N/m<sup>2</sup>-day**



### Clarifier Design Considerations

Clarifier design for activated sludge plants must consider the solids loading rate and the overflow rate. In an MBBR system similar to that operated during Phase II, the solids loading rate will not factor into design. The suspended solids concentration in the MBBR effluent is only 2-4% of that expected from a comparable activated sludge facility. MBBR systems can use smaller clarifiers vis-à-vis activated sludge when the clarifier design for the latter facility is based on the solids loading rate.

### Waste Solids Production

Waste solids production during the Phase II study was calculated from the flow, effluent TSS, and influent and effluent COD data. The results were expressed in terms of kg of waste solids produced per kg of COD removed. Comparable values were calculated for the Sanitation Districts' water reclamation plants. The results are compared in Table 8. Solids production was lower for the MBBR. Lower solids production is a characteristic of systems that operate at a long solids retention time. The higher solids inventory in these systems leads to a larger fraction of the COD being consumed for endogenous respiration. Hence less COD is available for net growth. The lower solids production rate in the MBBR has downstream benefits in terms of reducing the volume of digester capacity needed and reducing the mass of digested solids that require disposal.

**Table 8 – Waste Solids Production**

|                                                           | Solids Yield<br>(kg Waste Solids/kg COD removed) |           |
|-----------------------------------------------------------|--------------------------------------------------|-----------|
|                                                           | Average                                          | Range     |
| MBBR                                                      | 0.26                                             | 0.14-0.34 |
| Existing Sanitation Districts<br>Water Reclamation Plants | 0.32                                             | 0.27-0.39 |

## CONCLUSIONS

The pilot plant demonstration conducted at the Palmdale WRP found that MBBR was an effective technology for nitrifying the high TKN, low BOD wastewater discharged from the primary oxidation ponds, and for removing BOD and nitrogen from a municipal primary effluent.

The Phase I study showed:

- A well-operated MBBR was capable of reducing influent  $\text{NH}_3\text{-N}$  levels from  $> 20$  mg N/L to less than 1 mg N/L.
- The first stage of a two-stage MBBR can sustain nitrification at an average rate of 970 mg N/m<sup>2</sup>-day. Efficient nitrification in an MBBR requires that the dissolved oxygen concentration be maintained at levels higher than those typically used in activated sludge plants that nitrify.
- The nitrification rate in an MBBR varies linearly with the dissolved oxygen concentration when the bulk liquid  $\text{NH}_3\text{-N}$  concentration is greater than 3 mg N/L. The dependence of the nitrification rate on temperature and dissolved oxygen concentration is described by the equation:

$$r_N = 213.6 \bullet (DO - 1.15) \bullet 1.047^{(T-20)}$$

where  $r_N$  is the nitrification rate, and has units of mg N/m<sup>2</sup>-day, DO is expressed in mg/L and T is the temperature in °C.

- An effluent  $\text{NH}_3\text{-N}$  concentration below 1 mg N/L can be achieved when the  $\text{NH}_3\text{-N}$  loading is limited to 650 mg N/m<sup>2</sup>-day at a temperature of 18°C. The Arrhenius temperature correction factor of 1.047 can be used to correct this loading rate for other design temperatures.
- Good nitrification performance can be achieved at temperatures near 12°C by increasing aeration to maintain high dissolved oxygen concentrations. The power costs for increasing aeration are mitigated by the improved oxygen transfer efficiency that occurs at lower temperature.

The Phase II study found:

- MBBR can remove on average  $0.15 \text{ kg N/m}^3\text{-day}$  (reactor volume basis). This rate is greater than that observed at seven full-scale activated sludge plants that practice nitrogen removal.
- The effluent  $\text{NO}_2\text{-N}$  plus  $\text{NO}_3\text{-N}$  concentration from an MBBR operating at  $27.5^\circ\text{C}$  and under anoxic conditions can be reduced to below  $1 \text{ mg N/L}$  when the  $\text{NO}_2\text{-N}$  plus  $\text{NO}_3\text{-N}$  loading rate is less than  $930 \text{ mg N/m}^2\text{-day}$  (media surface area basis)
- The solids production rate in an MBBR is lower than that for activating sludge plants practicing nitrogen removal. The MBBR generated  $0.26 \text{ kg}$  of solids for every  $\text{kg}$  of COD removed. This is lower than the  $0.32 \text{ kg solids/kg COD removed}$  calculated for seven full-scale activated sludge plants that practice nitrogen removal.

MBBR appears capable of achieving nitrogen removal objectives in a smaller overall bioreactor volume. Savings on clarifier volume may also be possible. However, these advantages must be weighed against the costs for purchasing the MBBR media and higher energy costs for aeration.

## REFERENCES

- Rittman, B. E. and McCarty, P. L. (2001), *Environmental Biotechnology: Principles and Applications*, McGraw-Hill, Boston, Massachusetts.
- Metcalf and Eddy (2003), *Wastewater Engineering: Treatment and Reuse*, International Edition, McGraw-Hill, Boston, Massachusetts.
- Hem, L. J., Rusten, B., and Odegaard, H. (1994) Nitrification in a Moving Bed Biofilm Reactor, *Water Research*, **28**, 1425.
- Odegaard, H., Rusten, B. and Westrum, T. (1994) A New Moving Bed Biofilm Reactor-Applications and Results, *Water Science and Technology*, **29**, 157.