Moving Bed Bioreactor (MBBR) Design Guidelines

Introduction

Moving Bed Biofilm Reactors (MBBRs) were developed in Europe in the early 1990s. The initial concept was to take advantage of the benefits of both the attached-growth biofilter and the activated-sludge treatment processes, while addressing the limitations of each. Similar to activated-sludge systems, MBBRs use the entire vessel for biomass growth and development without the need for a return activated-sludge (RAS) or recycle loop.

These guidelines provide design information and guidance for applications using an MBBR treatment system under aerobic or anoxic conditions. There are several sources for determining MBBR loading and sizing, and these guidelines rely primarily on one of the most prominent by Metcalf and Eddy. Other resources include Bitton; Crites and Tchobanoglous; and the Water Environment Federation. (See "References" at the end of this document.)

MBBR Unit Descriptions

Orenco's MBBR units are completely pre-assembled in insulated fiberglass-reinforced polymer (FRP) composite vessels. The vessel size and configuration depend on system sizing requirements and site characteristics. Inlet and outlet piping are included with each unit, with configuration dependent on the requirements of the project. See Table 1 for typical vessel specifications.

Installation methods for MBBR units include partial burial, bermed, or free-standing. Typical units are installed with the top of the unit at 24-36in (610-910mm) above grade or berm for ease of maintenance; antibuoyancy measures are available for areas with high groundwater. Specific site conditions may require some custom design work; contact Orenco's Systems Engineering Team for details.

Media (carrier) volume can be up to 70% of the vessel. Orenco typically recommends 30-50% media volume to allow for additional media in the event that project flows, influent waste strengths, or permit requirements change. Air is pumped into a grid of pipes located at the bottom of the vessel, through coarse orifices or fine-bubble diffusers, to distribute oxygen for treating the waste stream and air for mixing the media. Media mixing is essential to shear any excess growth from the carriers, which ensures the carriers maintain a thin layer of biological film on their surfaces.

Table 1. Typical Orenco MBBR Vessel Specifications

Parameter	MBBR08	MBBR10	MBBR12
Length, ft (m)	14-42 (4.2-12.8)	14-50 (4.2-15.2)	14-50 (4.2-15.2)
Outside width, in (mm)	87 (2210)	120 (3050)	144 (3660)
Inside width, in (mm)	78.25 (1988)	107.25 (2725)	131.25 (3334)
Height, in (mm)	92 (2337)	120-132 (3050-3350)	120-144 (3050-3660)
Max. liquid depth, ft (m)	6.5 (2.0)	9.5 (2.9)	10.5 (3.2)
Top wall thickness, in (mm)	4.375 (111)	6.375 (162)	6.375 (162)
Side wall thickness, in (mm)	4.375 (111)	6.375 (162)	6.375 (162)
Floor thickness, in (mm)	4.375 (111)	4.375 (111)	4.375 (111)
Optional floor thickness, in (mm)	n/a	6.375 (162)	6.375 (162)
Baffle wall thickness, in (mm)	2.375 (60.3)	4.375 (111)	4.375 (111)
Optional baffle wall thickness, in (mm)	n/a	6.375 (162)	6.375 (162)
Dry weight, lbs (kg)	up to 12,000 (5440)	up to 30,000 (13,600)	up to 40,000 (18,144)
Installed footprint, actual, ft^2 (m^2)	112-336 (10.4-31.2)	140-500 (13.0-46.5)	168-600 (15.6-55.8)

Design Basis

These guidelines provide a list of the design parameters necessary to determine the suitability of Orenco products to a given project and for forming the basis of the system's design. To ensure that the system is designed properly for a given application, it is critical to first determine the design basis. The design basis for any treatment system consists of careful evaluation of several parameters that will affect the system's design and subsequent performance. Orenco's *Engineered Project Questionnaire*, NFO-ATX-ADM-2, is available to assist in identifying and characterizing these parameters. You can find it at www.orenco.com, or you can contact Orenco or your local Orenco dealer for a copy.

Average Day and Maximum Day Flows

Flows may be defined or calculated differently by application and local regulation; however, the following definitions are used in these guidelines:

Design Average Flow (Q_A)

Design average flow is the average of the daily volume to be received for a continuous 12-month period, expressed as a volume per day. For facilities with critical, seasonal periods of high hydraulic loading, such as recreational areas or campgrounds, Q_A is based on the daily average flow during the seasonal period. Calculations vary by application and local regulation; be sure to check with the regulating authority if the flow calculations are unclear.

Design Basis, cont.

Design Maximum Flow (Q_M)

Design maximum flow is the largest volume of flow to be received during a continuous 24hr period, expressed as a volume per day. It is highly dependent on application and collection technology used. For liquid-only sewer (LOS), septic tank effluent pump sewer (STEP), grinder sewer, and vacuum sewer, a typical Q_M value is two times the design average flow, or $2Q_A$. For gravity sewer applications, a typical value for Q_M is four times the design average flow, or $4Q_A$, for new construction and can range to over ten times ($10Q_A\pm$) for existing systems.

Carefully evaluate any existing flow information, textbook estimating methods, and regulatory requirements when establishing this design parameter.

Effluent Wastewater Strength

Organic Constituents in Wastewater

The two primary organic constituents in wastewater that are used to determine applicability and sizing of Orenco treatment systems are Biochemical Oxygen Demand (**BOD_5**) and Total Suspended Solids (**TSS**). In order to determine the waste load to an MBBR treatment system, it is necessary to determine the constituent concentrations entering the first MBBR process. These influent constituents are typically measured either in filtered or screened raw wastewater or after the primary treatment stage.

Nitrogen Constituents in Wastewater

The principal forms of nitrogen found in wastewater are Organic Nitrogen (**Organic-N**), Ammonia Nitrogen (**NH_3-N**), Ammonium Nitrogen (**NH_4-N**), Nitrite Nitrogen (**NO_2-N**), and Nitrate Nitrogen (**NO_3-N**). These are expressed either individually or as components of the following:

- **Total Kjeldahl Nitrogen** (**TKN**), which is the sum of Organic-N + NH_3-N
- **Total Inorganic Nitrogen** (**TIN**), which is the sum of NH_3-N + NO_2-N + NO_3-N
- **Total Nitrogen** (**TN**), which is the sum of TKN + NO_2-N + NO_3-N

As with organic constituent concentrations, nitrogen constituent concentrations must be quantified after the primary treatment stage to determine the waste load to the AdvanTex® Treatment System and are listed as primary-treated effluent throughout this document. A thorough understanding of the nitrogen cycle and how it works within the wastewater system is important when designing a system to treat for these parameters. Treatment for NH_3-N and TKN occurs through an aerobic process while treatment for NO_3-N, TIN, and TN occurs through a combination of aerobic and anoxic processes. A brief description of the processes follows.

Ammonification

Nitrogen is usually introduced into the wastewater system as Organic-N and NH_4-N. Organic-N (including feces, urea, and other animal and vegetable matter) in wastewater is converted into NH_4-N by ammonification. In ammonification, proteins, amino acids, and other nitrogen-containing compounds are biochemically degraded by heterotrophic bacteria. Ammonification typically occurs in primary tankage and transport lines as well as the secondary treatment process. Because of this, a measurement of ammonia in raw wastewater may be significantly lower than the true value. In these instances, TKN is a better measure of overall nitrogen content and should be used when determining waste load to the MBBR treatment system.

Nitrification

Organic removal must be accomplished prior to nitrification in an MBBR treatment process. An ammonium-oxidizing autotrophic bacteria, Nitrosomonas, converts ammonium to nitrite in the first step of nitrification and requires 3.43g O_2/g N_2 produced. A nitrite-oxidizing bacteria, Nitrobacter, converts nitrite to nitrate in the second step of nitrification and requires 1.14g O_2/g NO_3 produced. Both of these are aerobic processes, requiring 4.57g O_2/g NH_4 nitrified. The nitrogenous oxygen demand ranges between 45 and 60g O_2/person•day (0.1 and 0.13lb O_2/person•day).

Denitrification

Denitrification occurs when nitrate is converted to nitrogen gas by heterotrophic bacteria under anoxic conditions, typically when dissolved oxygen (DO) is less than 0.5mg/L. (See the “Nitrification Treatment” section for information regarding pH and temperature effects on nitrification and denitrification.)

Design Basis, cont.

Discharge Treatment Levels and Sampling Requirements

Discharge treatment levels and sampling requirements play a significant role in treatment facility design. Secondary treatment (effluent concentrations of $cBOD_5$ and TSS of ≤ 30mg/L based on a 30 day average) is a simple process which typically requires only a two-stage organic removal MBBR followed by AdvanTex for polishing. Additionally, advanced secondary treatment ($cBOD_5$ and TSS of ≤ 10mg/L based on a 30 day average) can be accomplished in the same manner. Many permits now require some higher level of nitrogen treatment as well as providing values of "not to exceed" in place of "30 day average" or "30 day arithmetic mean." A safety factor of some kind is applied in these instances (or additional processes added), so the discharge parameters are not exceeded even under maximum day flow conditions or maximum day primary-treated effluent concentrations.

System Expansion and Potential Permit Changes

Permits are limited in duration. Discharge requirements for treated effluent have become stricter over the past two decades. Many permit renewals now ask for measurement of various constituents not included in the original design of the treatment facility. Orenco recommends that designers use incremental engineering to plan and provide for space for potential future treatment upgrades, including facility expansions and permit modifications. With an MBBR, this can often be handled by initially using a conservative media fill volume (20-30%), providing the ability to add additional media in the future. By understanding the various stages used in Orenco treatment systems, the designer can lay out the treatment facility in a manner that allows for additional stages in the event that a planned build-out or future permit renewal requires it. (See the "Treatment System Configurations" and "Process Stages – MBBR Treatment Systems" sections for more information.)

Highly Variable or Seasonal Flow Considerations

Hundreds of Orenco's treatment systems are installed in parks, campgrounds, resorts, and lodges that experience highly variable flows (or complete shutdowns for long periods) due to seasonal use. Packed-bed filters, such as Orenco's AdvanTex Treatment Systems, are ideally suited for these applications. For highly variable flows, an MBBR can precede an AdvanTex system to provide additional treatment and allow for higher loading rates.

The operations and maintenance (O&M) manual provided with each Orenco treatment system can help guide operators regarding appropriate O&M for systems with highly variable or seasonal flows, including the use of trending to automatically adjust recirculation ratios. For more information on determining which O&M method is best for a particular highly variable or seasonal flow application, contact Orenco.

Treatment System Configurations

This section explains the three most common treatment system configurations using an Orenco MBBR Treatment System. Flow, available land footprint, primary-treated effluent constituent concentrations, and discharge permit requirements determine the appropriate configuration for the system. Each configuration shows the applicable treatment stages used and where to find the proper system sizing information. Clarification is required with each MBBR configuration.

For systems with restaurant waste contributions, adequate grease tankage is necessary to ensure that the maximum fats, oils, and greases (FOG) contribution to the MBBR treatment system does not exceed 100mg/L. Levels above 100mg/L tend to prematurely clog the carriers and prevent adequate treatment of wastewater constituents for effective biological breakdown.

(See the "MBBR Reactor Sizing and Hydraulic Retention Time" and "MBBR Reactor Calculations" sections for determining loading parameters and reactor sizing. See the "Nitrification Treatment" section for more information on pH.) Contact Orenco or your Orenco dealer for assistance with questions regarding appropriate treatment configurations or kinetic calculations.

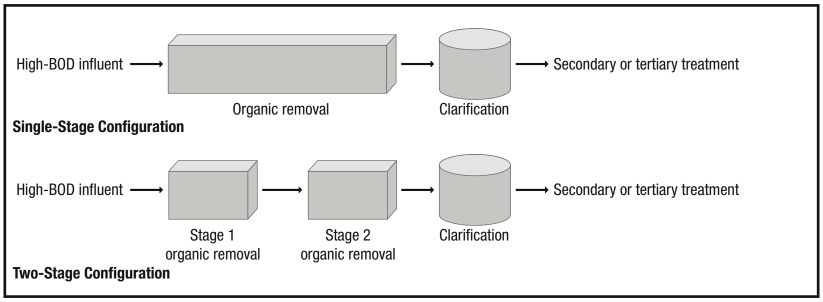


Figure 1. Basic Organic Removal Configurations

Organic Removal

Figure 1 shows the typical MBBR configurations for organic constituent removal. Organic removal is the simplest form of advanced treatment, typically requiring only primary and secondary treatment. MBBRs can be used as single- or two-stage roughing filters followed by clarification for BOD_5 and TSS removal prior to a secondary or polishing filter. MBBR organic stages used for roughing down a waste stream can typically achieve treatment levels of 50-100mg/L BOD_5/$cBOD_5$ and TSS (based on 30 day average or 30 day arithmetic mean).

A single-stage roughing filter configuration is often used if the removal requirement is 75% or less, while a two-stage configuration is used for removal rates greater than 75%. Two-stage systems allow the operator more flexibility to alter the flux rate (loading rate) in each of the two stages to achieve treatment target objectives.

Treatment System Configurations, cont.

Nitrification

Figure 2 shows typical single- or two-stage MBBR configurations followed by clarification for nitrification of ammonia. A nitrifying MBBR can typically achieve 90-95% nitrification of ammonia (based on 30 day average or 30 day arithmetic mean) for projects where organic removal is nearly complete, but ammonia removal is required due to restrictive (> 90% removal) NH_3-N or TKN discharge limits. Two-stage systems allow the operator more flexibility to alter the flux rate in each of the two stages to achieve target treatment objectives.

Nitrification occurring in MBBR systems is heavily influenced by the alkalinity required to buffer the process (7.14mg/L alkalinity per 1mg/L NH_3-N). For complete nitrification, pH levels of 7.5 to 8.5 are ideal, and pH levels for all applications should be buffered to remain above 7. A supplemental alkalinity feeder may be necessary immediately preceding the nitrification treatment stage(s) to ensure sufficient alkalinity for nitrification.

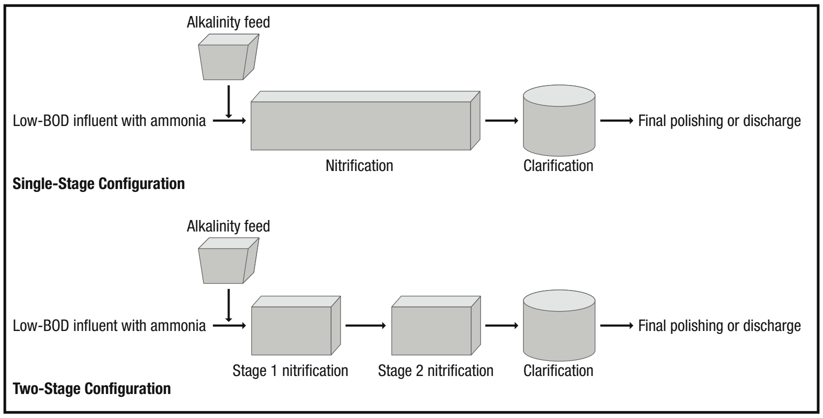


Figure 2. Basic Nitrifying Configurations

Post-Anoxic Denitrification

Figure 3 shows a typical MBBR configuration for post-anoxic dentrification. MBBRs can be used to denitrify highly nitrified waste streams that require denitrification. Denitrifying MBBRs can be added to the end of most secondary processes where complete or near complete nitrification has occurred.

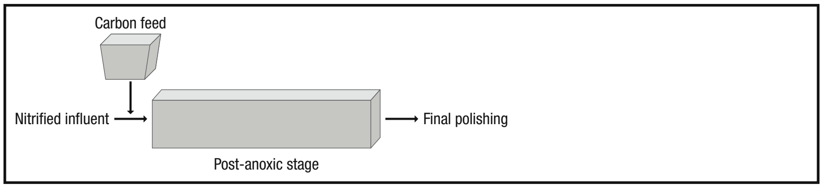


Figure 3. Post-Anoxic Denitrification

Carbon is added in the post-anoxic stage to maintain the proper carbon-to-nitrogen (**C:N**) ratio for denitrification. C:N ratios need to be greater than 4:1 and preferably in the 6:1 range to ensure that complete denitrification occurs. Depending on the permit limits, post-anoxic denitrifying MBBRs will require a polishing filter to remove any unused carbon (**BOD**) added for denitrification.

Organic and Advanced Ammonia Removal

Figure 4 shows typical MBBR configurations for organic removal with advanced ammonia removal. A three- or four-stage MBBR system is usually necessary for wastewater systems requiring both organic and ammonia removal due to restrictive (> 90% removal) NH_3-N or TKN discharge limits. When incoming organic levels are greater than 300mg/L, a pre-anoxic stage should be considered to remove TN and reduce the BOD load prior to the organic removal stage(s).

The organic load must first be removed for the MBBR to completely nitrify the waste stream. This is accomplished in a single- or two-stage configuration, depending on the incoming organic load. Typically, a low waste strength of 180±mg/L BOD_5 can be handled by a single stage, while a two-stage system is often preferable above this value.

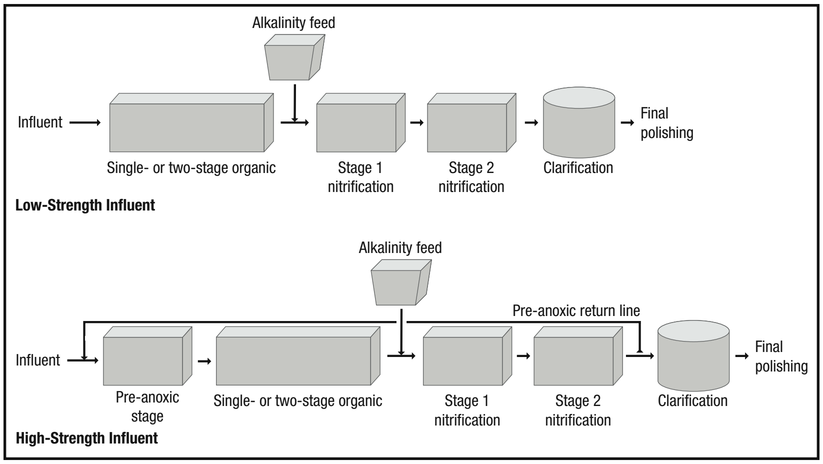
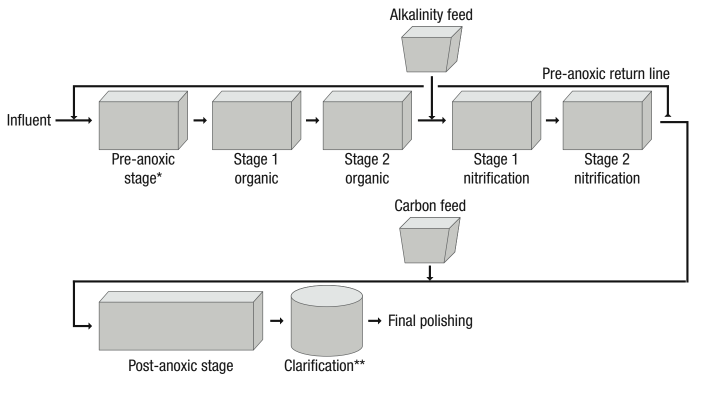


Figure 4. Basic Organic Removal and Advanced Nitrifying Configurations

Treatment System Configurations, cont.

Nitrification in MBBR systems is heavily influenced by the alkalinity required to buffer the process (7.14mg/L alkalinity per 1mg/L NH_3-N). For complete nitrification, pH levels of 7.5 to 8.5 are ideal, and pH levels should be buffered to remain above 7 for all applications. A supplemental alkalinity feeder may be necessary to ensure sufficient alkalinity for nitrification of ammonia. Using a pre-anoxic stage helps buffer pH; denitrification in this stage will return as much as 50% of the alkalinity consumed during nitrification. In addition, readily available BOD is consumed in the pre-anoxic denitrification stage, reducing the BOD load to the secondary treatment unit.

Most application types provide adequate carbon in the influent stream to achieve denitrification and subsequent alkalinity return, but it is best to ensure that there is enough alkalinity added without relying on this occurrence. As operational data becomes available for the specific treatment system – demonstrating the return of alkalinity through denitrification – alkalinity feed rates can be adjusted downward.



* A pre-anoxic stage should be evaluated on all projects requiring total nitrogen reduction
** Clarification can be placed between nitrification and post-anoxic stages to reduce DO levels before denitrification

Figure 5. Complete MBBR System with Organic Removal, Nitrification, and Denitrification

Organic Removal, Nitrification, and Total Nitrogen Removal

Figure 5 shows a complete MBBR system with organic removal, nitrification, and denitrification for wastewater systems with permit limits for BOD_5 or $cBOD_5$ and TN, TIN, or NO_3-N requiring greater than 60% nitrogen reduction.

The nitrification occurring in the MBBR treatment stage is heavily influenced by the alkalinity required to buffer the process (7.14 mg/L alkalinity per 1 mg/L of ammonia-nitrogen). For complete nitrification, pH levels of 7.5 to 8.5 are ideal, and pH levels should be buffered to remain above 7 for all applications. The use of the pre-anoxic stage benefits overall operation of the system since denitrification in this stage will return as much as 50% of the alkalinity consumed during nitrification. A supplemental alkalinity feeder may still be necessary immediately preceding the AdvanTex treatment stage to ensure sufficient alkalinity for nitrification.

Carbon addition should be balanced to the wastewater flows to ensure C:N ratios are appropriate. C:N ratios need to be greater than 4:1 and preferably in the 6:1 range to ensure that denitrification occurs. Carbon is added in the post-anoxic stage to maintain the proper C:N ratio. Carbon addition in the pre-anoxic stage is also recommended for applications requiring greater than 80% removal of nitrogen.

An AdvanTex polishing unit is used after the post-secondary anoxic stage to remove excess $cBOD_5$ prior to discharge for permits with stringent organic removal requirements.

Process Stages – MBBR Treatment Systems

Primary Treatment

In decentralized systems, the primary treatment stage typically includes wastewater collection; the segregation, accumulation, and storage of settleable and floatable solids (sludge and scum); the digestion of organic matter; and the discharge of primary-treated effluent. Passive, energy-free primary tankage provides the most cost-efficient method of primary treatment available for nonindustrial sewage; BOD removal of >50% and TSS removal of >90% (when using an effluent filter) are typically accomplished with passive primary treatment. Primary treatment can be accomplished in several ways prior to the MBBR treatment system(s).

A primary clarifier is commonly used in systems with large flows. A primary clarifier typically removes 90-95% of settleable solids, 40-60% of suspended solids, and 30-40% of BOD from the waste stream. Light particles typically float to the top where they are skimmed from the surface. Collected sludge is transferred to a process where it can be digested or further dewatered. The clear zone is moved forward to the headworks of the MBBR system.

Large particulate matter is typically removed through the use of screens or filters along with a trash tank in systems with small flows. Manufacturers generally recommend no larger than 6mm spacing in screens if primary treatment is also provided. Finer screening (3mm or less) is mandatory in instances where primary treatment is not provided (WEF 2010, chap. 5 sec. 3.3).

Wastewater entering the MBBR must have a FOG concentration below 100 mg/L and be free of any particles greater than 6mm (preferably 3mm). The design engineer is responsible for selecting the primary treatment technology and assessing influent parameters for treatment.

Process Stages – MBBR Treatment Systems, cont.

Flow Equalization

The flow equalization (**EQ**) stage consists of a tank or tanks fitted with a pumping system that is timed-dose controlled. It typically follows primary treatment. EQ provides stability by leveling out peaks in flow and allowing consistent loading of the treatment system. It is strongly recommended for systems with variable flow patterns and restrictive discharge limits, and is especially important for systems that have highly variable flow patterns due to usage (for example, resorts and churches) or collection method (for example, conventional gravity collection).

Design Notes and Special Considerations

By their nature, effluent sewer collection systems inherently provide significant flow equalization. The addition of EQ tanks at the treatment site is only necessary for systems with extreme flow fluctuations (for example, fairgrounds, racing venues, etc.) or highly restrictive permit requirements when using this collection method. EQ tank sizing recommendations vary for systems with significant fluctuations in flow. For schools and churches, Orenco typically recommends dividing the system's total weekly flow by six and using this value as Q_A, with one day allowed for recovery. Using this technique, an EQ tank equal to Q_M is generally adequate, but calculations should be performed to verify the tank sizing requirement. Contact Orenco for assistance with EQ tank sizing.

Pre-Anoxic Treatment

A pre-anoxic treatment stage benefits all applications and is essential for applications with high-strength waste (organic or nitrogen concentrations), restrictive permit limits, or applications desiring higher-quality effluent and enhanced overall removal performance. This stage consists of recirculating a portion of the filtrate from the MBBR nitrification stage(s) to an anoxic zone in a separate pre-anoxic tank. It tends to balance and lower concentrations by blending primary-treated effluent with highly nitrified effluent from the MBBR nitrification stage(s), providing an environment for denitrification of a portion of the nitrified filtrate.

Surface Area Loading Rate (**SALR**) or flux rate for nitrogen removal in this stage ranges from 0.5-1.0g $NO_3/m^2 \bullet d$ (0.012-0.024lbs $NO_3/ft^2 \bullet d$). In this expression, the area is the surface area of the media in the unit. Orenco recommends only using the protected surface area when calculating media requirements. An SALR of 0.5g $NO_3/m^2 \bullet d$ (0.012lbs $NO_3/ft^2 \bullet d$) is normally used when relying on the natural BOD in the influent waste stream; a higher SALR can be used when a carbon source is provided via a chemical feed system.

DO returned in the recycle flow can have a significant influence on performance with MBBR systems. Elevated bulk DO levels can be required for the nitrification stage of the MBBR process. DO levels in the pre-anoxic treatment stage should be kept below 0.5mg/L (preferably <0.2mg/L) to ensure that nitrate becomes the primary oxygen source for microorganisms. The pre-anoxic return ratio (**R_{NOX}**) is the ratio of flow of the pre-anoxic return loop in relation to Q_A. For most applications, R_{NOX} is equal to 1± and therefore the return flow to the pre-anoxic stage (**Q_{RNOX}**) is equal to Q_A. Where influent wastewater characteristics are suitable for pre-denitrification, nitrogen removal performance can usually range between 50 and 70% (WEF 2010, chap. 5 sec. 3.1.6.1).

The pre-anoxic return line is a convenient place to add alkalinity while simplifying the overall system layout. It can also be used to introduce supplemental carbon while still keeping the design simple. The establishment of denitrification in this stage reduces organic and nitrogen levels while returning about 50% of the alkalinity consumed during the nitrification stage(s) (3.57mg/L alkalinity per 1mg/L NO_3-N denitrified). Supplemental carbon addition in the pre-anoxic stage should be considered for systems requiring significant total nitrogen reduction (>80%) with high nitrogen values in primary-treated effluent, resulting in low C:N ratios (<4:1), with the understanding that further denitrification typically occurs in the post-anoxic treatment stage. (See the "Post-Anoxic Treatment" and "Supplemental Chemicals" sections for more information.)

Organic Treatment

Single-Stage or First-Stage Organic Removal

Single-stage or first-stage organic removal is typically configured to remove 75-90% of BOD_5. SALRs can vary between 5-20g $BOD_5/m^2 \bullet d$ (0.119-0.476lbs $BOD_5/ft^2 \bullet d$), with an SALR of 12g $BOD_5/m^2 \bullet d$ (0.285lbs $BOD_5/ft^2 \bullet d$) being commonly used.

Table 2. Surface Area Loading Rates (SALRs) for MBBRs

Application	BOD SALR ($g/m^2 \bullet d$)
High rate (75-80% BOD removal)	>20
Normal rate (80-90% BOD removal)	5-15
Low rate (preceding nitrification)	5

(WEF 2010, chap. 5 sec. 3.1.2)

Table 2 shows that an SALR of greater than 20g $BOD_5/m^2 \bullet d$ (0.475lbs $BOD_5/ft^2 \bullet d$) can be used for a single-stage roughing application prior to secondary treatment. It is possible to remove 80-90% of BOD_5 at SALRs of 5-15g $BOD_5/m^2 \bullet d$ (0.119-0.356lb $BOD_5/ft^2 \bullet d$), though most calculations assume 75% removal. SALRs are kept below 5g $BOD_5/m^2 \bullet d$ (0.119lbs $BOD_5/ft^2 \bullet d$) using a single-stage configuration preceding a nitrification stage.

Process Stages – MBBR Treatment Systems, cont.

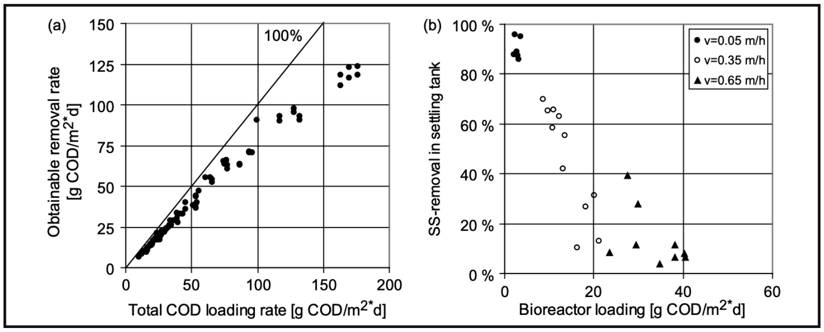


Figure 6. Loading Rate Effect on COD Removal Rate and Settleable Solids Removal (Reprinted from WEF 2010, chap. 5 sec. 3.1.2)

Figure 6 shows the relationship between SALR, surface area removal rate (**SARR**), and suspended solids removal. Generally, SALR is limited to 10-12g BOD$_5$/m^2•d (0.237-0.285lbs BOD$_5$/ft^2•d) unless there are additional processes to follow for removing suspended solids downstream. As graph (b) in Figure 6 shows, solids removal in the settling tank tends to fall below 60% when these values are exceeded.

Second-Stage Organic Removal

The purpose of the second stage is to complete organic removal and prepare the effluent for nitrification, if necessary. It is configured to remove approximately 90% of the BOD$_5$ remaining after the first stage. In applications for organic removal without a nitrification stage, SALR can vary between 5-15g BOD/m^2•d (0.119-0.356lbs BOD/ft^2•d), with 12g BOD/m^2•d (0.285lbs BOD/ft^2•d) being commonly used. The SALR in the second organic removal stage is kept below 5g BOD/m^2•d (0.119lbs BOD/ft^2•d) when followed by a nitrification stage, with 4g BOD/m^2•d (0.095lbs BOD/ft^2•d) being commonly used.

Dissolved oxygen in this stage typically ranges from 2-3mg/L. Bulk DO values above 3mg/L do not improve SARR (WEF 2010, chap. 5 sec. 3.1.1). (See the "MBBR Reactor Calculations" section for organic kinetic growth coefficients and calculations.)

Nitrification Treatment

Five significant factors impact the performance of the nitrogenous reactors: organic loading, DO concentrations, ammonium concentration, wastewater temperature, and pH and available alkalinity. It is critical that the organic stages remove all BOD prior to the nitrification reactor(s).

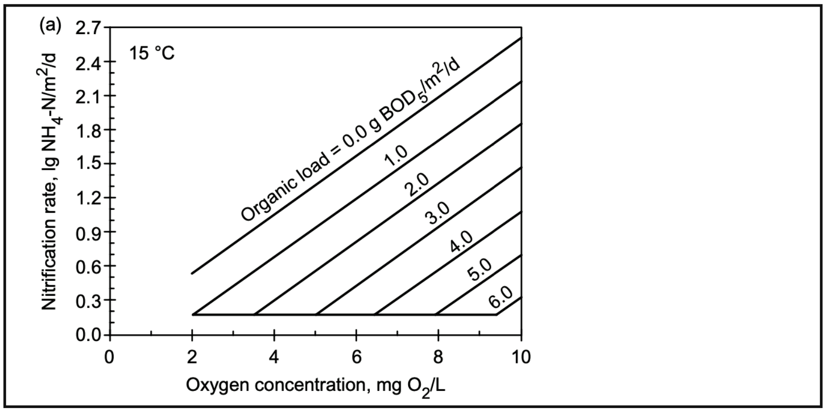


Figure 7. Impact on Dissolved Oxygen (DO) by BOD Load Carryover in Nitrification (Reprinted from WEF 2010, chap. 5 sec. 3.1.4)

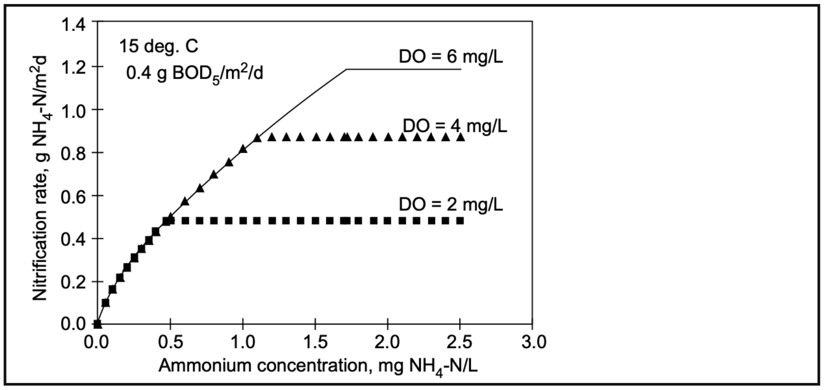


Figure 8. Dissolved Oxygen (DO) Effect on Nitrification Rate
(Reprinted from WEF 2010 chap. 5 sec. 3.1.5)

Organic Loading

Figure 7 shows the impact of the organic load carried through to the nitrification reactor(s) on the bulk DO requirement. For example, if incomplete organic removal occurred in the organic reactor(s), resulting in a nitrification reactor SALR of 3g BOD$_5$/m^2•d, and an SALR of 0.9g NH$_3$/m^2•d was selected based upon the presumption that complete organic removal occurred in the organic reactor(s), the required DO in the nitrification reactor would be 8mg O$_2$/L. If complete BOD removal had occurred in the organic reactor(s), the required DO in the nitrification reactor would be 4mg O$_2$/L. Incorrectly sized organic reactors can require larger blowers, air delivery lines, and associated valving, which can impact energy costs significantly in nitrification treatment stages.

DO and Ammonium Concentrations

Figure 8 shows that DO has a significant effect on the nitrification rate until ammonium levels drop to very low concentrations. DO in this stage typically ranges from 3-6mg/L, with 4mg/L being most commonly used.

Process Stages – MBBR Treatment Systems, cont.

Wastewater Temperature

Figure 9 shows that the effect of temperature in the liquid stream and treatment media on nitrification and denitrification rates should be considered in determining reactor loading and removal rates. Temperature affects biological kinetics, rate of diffusion of substrate into and out of the biomass, and viscosity of the liquid, which in turn may influence the effect of shear energy on biofilm thickness, as well as affect the solubility of oxygen in the liquid. These impacts are taken into account in determining the reactor's SALR and DO requirements.

(See the "MBBR Reactor Calculations" section for specific adjustments.)

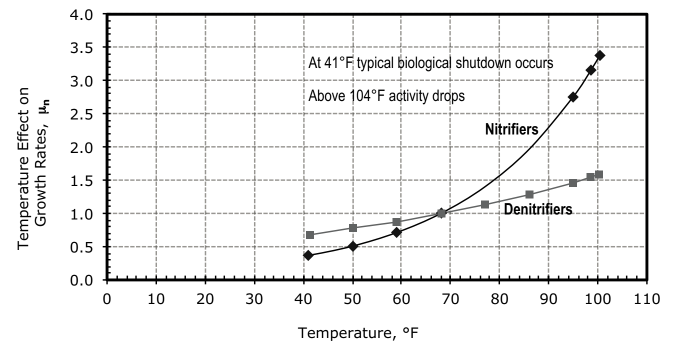


Figure 9. Temperature Effect on Nitrification and Denitrification

pH and Available Alkalinity

Figure 10 shows that pH is extremely important for nitrification. The effective reaction rate (**R_N**) is 0.95 at a pH of 8±, dropping to 0.47 at a pH of 7, and dropping precipitously to 0.15 at a pH of 6, with nitrification effectively ceasing at a pH of 5. The use of additional alkalinity to buffer the process is critical for all nitrogen removal configurations, and an alkalinity feed system should be sized to provide a minimum targeted residual of 80mg/L, with a preferred residual target of 100mg/L. (See the "Supplemental Chemicals" section for more information.)

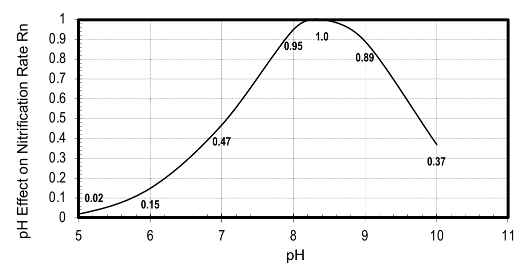


Figure 10. pH Effect on Nitrification Rate

First-stage nitrification is typically configured to nitrify approximately 50-60% of the incoming ammonia. For single-stage nitrification, the system can be configured for an SALR between 0.4-1.4g $NH_3/m^2 \bullet d$ (0.0095-0.033lbs $NH_3/ft^2 \bullet d$) and is based on the more conservative rate between the calculated DO limited flux rate and the ammonia limited flux rate. The ammonia limited flux rate typically controls this selection for single-stage nitrification; the DO limited flux rate is typically used for two-stage nitrification.

Second-stage nitrification is intended to complete nitrification. This stage is configured to remove approximately 99% of the NH_3 remaining after the first stage. The SALR or flux rate is typically the lower value of the ammonia limited flux rate and 1.4g $NH_3/m^2 \bullet d$ (0.033lbs $NH_3/ft^2 \bullet d$). (See "MBBR Reactor Calculations" for nitrogenous kinetic growth coefficients and calculations.)

Post-Anoxic Treatment

The post-anoxic treatment stage provides additional denitrification after secondary treatment in wastewater systems that require significant reductions in TN, TIN, or NO_3-N. Nitrified effluent from the nitrification stage(s) flows to an anoxic zone inside of the post-anoxic tank. BOD is consumed during the conversion of NO_3 to N_2 gas by facultative heterotrophic bacteria during post-anoxic denitrification. The N_2 gas is then returned to the atmosphere. A supplemental carbon feed unit is required for the post-anoxic stage to achieve the necessary C:N ratio for effective denitrification. SALRs in the post-anoxic stage range from 0.5 to 1.0g $NO_3/m^2 \bullet d$ (0.012 to 0.024lbs $NO_3/ft^2 \bullet d$) depending on the carbon source used.

Requirements for effective denitrification include:

- DO levels of less than 0.5mg/L (preferably less than 0.2mg/L) to ensure that nitrate becomes the primary oxygen source for microorganisms. (A clarification stage can be placed between the nitrification stage and the post-anoxic stage to ensure that these levels are achieved prior to the post-anoxic stage.)
- A C:N ratio of 4:1 to 8:1.
- Sufficient residual alkalinity (100mg/L±) in the secondary treatment stage to ensure optimum pH in the post-anoxic stage.

Process Stages – MBBR Treatment Systems, cont.

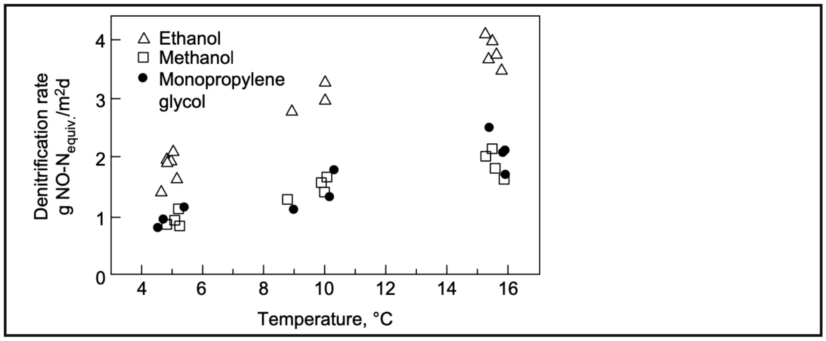


Figure 11. Carbon Source and Temperature Effect on Denitrification Rate (Reprinted from WEF 2010, chap. 5 sec. 3.1.6.3)

While Figure 9 shows that temperature has an impact on denitrification, Figure 11 shows that the carbon source can also have a significant impact on denitrification when waste stream temperatures are low.

For standard post-anoxic treatment meeting the conditions above, reduction of NO_3 through conversion to N_2 gas is approximately 80-90%. When sizing the reactor, use a removal rate of 98% in the calculations to conservatively determine the media and reactor volumes. (See “MBBR Reactor Calculations” for kinetic growth coefficients and calculations and “Supplemental Chemicals” for carbon feed options for denitrification.)

Clarification

The clarification stage settles solid particles out of the waste stream that are generated during mixing and shearing in order to keep a thin biological film on the carriers inside the MBBRs. The clarifier may be placed at the end of the system; however, it may also be placed between the nitrification stage(s) and the post-anoxic treatment stage to remove particulate matter and reduce DO levels prior to denitrification. Clarifier sizing is based upon Q_M divided by the surface overflow rate (**SOR**). Typical SORs for MBBRs range from 12.2-32.6m^3/m^2•d (300-800gal/ft^2•d), with 16.3m^3/m^2•d (400gal/ft^2•d) being commonly used. The equation used for this is:

$$A_{CLARIFIER} \approx Q_M / SOR$$

Polishing

In the polishing stage, secondary-treated effluent is often polished using a packed-bed filter, such as an AdvanTex unit. BOD_5 and TSS levels vary after clarification, based upon the MBBR configuration and flow patterns. Each application should be evaluated, and polishing added when necessary. For AdvanTex loading rates, see *AdvanTex Design Criteria: Commercial Treatment Systems*, NDA-ATX-1.

Influent Waste Strength Calculations and Conversions

Influent values are typically provided for BOD_5, TSS, and TKN or TN [and possibly chemical oxygen demand (**COD**), NH_3-N or NO_3-N]. However, in order to determine load on an MBBR, several other derivations of these influent values are necessary. Typical values for untreated domestic wastewater can be found in Table 3-18 on page 221 of Metcalf (2014). The estimation values and equations below can also be found in Metcalf (2014). The following influent parameters need to be determined in order to perform the necessary calculations:

Volatile suspended solids (**VSS_i**) in mg/L; measure, look up, or estimate at 70-80% of TSS:

$$VSS_i \approx 0.75 * TSS_i$$

Chemical oxygen demand (**COD_i**) in mg/L; measure, look up, or estimate using:

$$COD_i \approx 2.4 * BOD_{5i}$$

Biodegradable chemical oxygen demand (**$bCOD_i$**) in mg/L; estimate using:

$$bCOD_i \approx 1.6 * BOD_{5i}$$

Soluble chemical oxygen demand (**$sCOD_i$**) in mg/L; estimate using:

$$sCOD_i \approx 0.59 * bCOD_i,$$

Non-biodegradable chemical oxygen demand (**$nbCOD_i$**) in mg/L; calculate using:

$$nbCOD_i = COD_i - bCOD_i$$

Soluble BOD (**$sBOD_i$**) in mg/L; measure or calculate using:

$$sBOD_i = BOD_{5i} - 1.42 * VSS_i * (BOD_{5i} / bCOD_i)$$

Biodegradable particulate chemical oxygen demand (**$bpCOD_i$**) in mg/L; calculate using:

$$bpCOD_i = (bCOD_i / BOD_{5i}) * (BOD_{5i} - sBOD_i)$$

Influent Waste Strength Calculations and Conversions, cont.

Particulate chemical oxygen demand (**$pCOD_i$**) in mg/L; calculate using:

$$pCOD_i = COD_i - sCOD_i$$

Non-biodegradable volatile suspended solids in the effluent (**$nbVSS_i$**) in mg/L; calculate using:

$$nbVSS_i = (1 - bpCOD_i / pCOD_i) * VSS_i$$

MBBR Reactor Sizing and Hydraulic Retention Time

Unit sizing is dependent on the load (BOD for organic, TKN for nitrification, and nitrate for pre-and post-anoxic stages), the flux (loading) rate chosen, the protected surface area of the media selected, the media fill percentage, and the percent removal targeted in the stage. Contact Orenco for specific reactor sizing configurations.

The equation for determining media volume in m^3 is:

Media Volume = (Influent Mass * % Removal Target) / (Flux Rate * Media Surface Area)

The equation for determining reactor volume in m^3 is:

Reactor Volume = (Media Volume / % Fill)

The equation for determining the hydraulic retention time (**HRT**) in hours is:

$$HRT = [\text{Reactor Volume} - \text{Media Volume} * (1 - \%\ \text{Void})] / [Q_A * (1 + R_{NOX})] * (24hr/day)$$

(R_{NOX} is the ratio of return flow to average daily design flow, ranging from 0.5-2, with 1 being typical.)

MBBR Reactor Calculations

Depending on the particular configuration and stages selected, there are several key MBBR reactor calculations that need to be performed. For example, before the load can be determined for a pre-anoxic stage, it is necessary to determine the nitrate mass returned from the nitrification stage(s) for blending with the incoming nitrogen, which in turn is dependent on the nitrogen removed through solids in the organic treatment stages. The calculations use a number of coefficients. Table 3 and Table 4 list growth-rate coefficients used for heterotrophic and nitrogenous calculations.

Table 3. Heterotrophic Kinetic-Growth Coefficients (Metcalf 2002, Table 8-10)

Heterotrophic	Typical	Range
Maximum heterotrophic biomass yield, Y_H	= 0.45g VSS/g bCOD	0.3-0.5g VSS/g bCOD
Maximum heterotrophic substrate utilization rate, K_s	= 20mg/L	5-40mg/L
Endogenous decay rate coefficient at 20ºC, b_H or k_d	= 0.12g VSS/g VSS•d	0.06-0.15g VSS/g VSS•d
Maximum heterotrophic specific growth rate, μ_{max}	= 6g VSS/g VSS•d	3-13.2g VSS/g VSS•d
Fraction of biomass that remains as cell debris, f_d	= 0.15g	0.1-0.15g
Temperature activity coefficient, Θ **for** μ_m	= 1.07	1.03-1.08
Temperature activity coefficient, Θ **for** K_s	= 1	1
Temperature activity coefficient, Θ **for** b_H or k_d	= 1.04	1.03-1.08

Heterotrophic Temperature Adjustment Calculations

The equation for determining $b_{H,T}$ in g/g•d is:

$$b_{H,T} = b_{H,20} * (\Theta \text{ for } b_H \text{ or } k_d)^{(T-20)}$$

The equation for determining $\mu_{m,T}$ in g/g•d is:

$$\mu_{m,T} = \mu_{max} * (\Theta \text{ for } \mu_m)^{(T-20)}$$

The equation for determining $K_{s,T}$ in mg/L is:

$$K_{s,T} = K_s * (\Theta \text{ for } K_s)^{(T-20)}$$

T can be T_d, T_s, or T_w to represent the design, summer, or winter temperature of the waste stream in °C.

MBBR Reactor Calculations, cont.

Table 4. Nitrogenous Kinetic-Growth Coefficients (Metcalf 2002, Table 8-11)

Nitrogenous	Typical	Range
Maximum nitrogenous biomass yield, $\mathbf{Y_n}$	= 0.12g VSS/g NH_4	0.1-0.15g VSS/g NH_4
Maximum nitrogenous substrate utilization rate, $\mathbf{K_n}$	= 0.7mg/L NH_4	0.5-1.0mg/L NH_4
Endogenous decay rate coefficient at 20ºC, $\mathbf{b_{NH4}}$ or $\mathbf{k_{dn}}$	= 0.08g VSS/g VSS•d	0.05-0.15g VSS/g VSS•d
Maximum nitrogenous specific growth rate, $\boldsymbol{\mu_{mn}}$	= 0.75g VSS/g VSS•d	0.2-0.9g VSS/g VSS•d
Oxygen inhibiting coefficient, $\mathbf{K_o}$	= 0.5mg/L	0.4-0.6mg/L
Temperature activity coefficient, $\boldsymbol{\Theta}$ for $\boldsymbol{\mu_{mn}}$	= 1.1	1.06-1.123
Temperature activity coefficient, $\boldsymbol{\Theta}$ for $\mathbf{K_n}$	= 1.053	1.03-1.123

Nitrogenous Temperature Adjustment Calculations

The equation for determining $\mathbf{b_{N,T}}$ in g/g•d is:

$$b_{N,T} = b_{NH4} * (\Theta \text{ for } b_N \text{ or } k_d)^{(T-20)}$$

The equation for determining $\boldsymbol{\mu_{mn,T}}$ per day is:

$$\mu_{mn,T} = \mu_{max} * (\Theta \text{ for } \mu_m)^{(T-20)}$$

The equation for determining $\mathbf{K_{s,T}}$ per day is:

$$K_{s,T} = K_s * (\Theta \text{ for } K_s)^{(T-20)}$$

T can be $\mathbf{T_d}$, $\mathbf{T_s}$, or $\mathbf{T_w}$ to represent the design, summer, or winter temperature of the waste stream in °C.

Estimating Pre-Anoxic Stage Values

The mass of nitrate from the nitrification reactor(s) must be estimated in order to determine input values for the pre-anoxic stage. Nitrification is typically targeted for greater than 95%, so this is the value generally used to estimate the nitrate blend in the pre-anoxic reactor.

Determine the return value, in mg/L, of nitrate to the pre-anoxic reactor:

$$NO_3\text{-}N_{RNOX\text{-}C} = 0.95 * k_{NO3\text{-}N} * TKN_i * (1 + 0.05 * R_{NOX}) / (1 + R_{NOX})$$

where

$k_{NO3\text{-}N}$ is the conversion coefficient between TKN and NO_3-N, typically 1g NO_3-N/1g TKN

TKN_i is the influent Total Kjeldahl Nitrogen (TKN) in mg/L

(R_{NOX} is the ratio of return flow to average daily design flow, ranging from 0.5-2, with 1 being typical.)

Determine the nitrate blend in the pre-anoxic reactor:

$$NO_3\text{-}N_{blend\text{-}C} = (NO_3\text{-}N_i + NO_3\text{-}N_{RNOX\text{-}C}) / (R_{NOX} + 1), \text{ mg/L or g/m}^3$$

Determine the blend mass of nitrate to the pre-anoxic reactor:

$$NO_3\text{-}N_{blend\text{-}M} = NO_3\text{-}N_{RNOX\text{-}C} * Q_A, \text{ grams}$$

The media and liquid volume of the pre-anoxic reactor is based on the nitrate removal SALR. Nitrate removal in the pre-anoxic chamber is typically 90%. (See the “Pre-Anoxic Treatment” and “MBBR Reactor Sizing and Hydraulic Retention Time” sections for more information.) Using this value and the amount of nitrate present, the mass, in grams, of BOD_5 consumed in the pre-anoxic reactor can be determined:

$$BOD_{5\ PRE\text{-}A} = NO_3\text{-}N_{RNOX\text{-}M} * NO_3\text{-}N \text{ \% Removal} * BOD\text{:}NO_3\text{-}N_{RATIO}$$

MBBR Reactor Calculations, cont.

Determining BOD in Organic Stages

To convert concentration to mass, multiply the concentration (mg/L or g/m^3) by the flow (in m^3) and convert to grams:

$$1\text{mg/L} * (1000\text{L}/1\text{m}^3) * (1\text{g}/1000\text{mg}) = 1\text{g/m}^3$$

$$BOD_{5i} = BOD_{5\text{-CON}} * Q_A$$

When a pre-anoxic reactor is used, the BOD$_5$ available for treatment in the first organic stage, in grams, is determined by the following expression:

$$BOD_{5\ OS1i} = BOD_{5i} - BOD_{5\ PRE\text{-}A}$$

And when a pre-anoxic reactor is not used:

$$BOD_{5\ OS1i} = BOD_{5i}$$

Organic removal, in grams, in the first stage is expressed using:

$$BOD_{5\ OS1\text{-}R} = BOD_{5\ OS1i} * \%\ Removal_{BOD5\ OS1}$$

Therefore, BOD$_5$ available for treatment, in grams, in the second stage is:

$$BOD_{5\ OS2i} = BOD_{5\ OS1i} - BOD_{5\ OS1\text{-}R}$$

Organic removal in the second stage, in grams, is expressed using:

$$BOD_{5\ OS2\text{-}R} = BOD_{5\ OS12} * \%\ Removal_{BOD5\ OS2}$$

Determining Ammonia Available for Nitrification

Heterotrophic bacteria synthesis consumes nitrogen during the organic removal stage(s). To determine the nitrogen consumed in g/m^3 or mg/L, use equation 8-20 from page 721 of Metcalf (2014).

$$P_{X\ bio\ org\ VSS}/Q_A = [(Y_H * BOD) * (1 + f_d * b_H * SRT_{org})] / (1 + b_H * SRT_{org})$$

where

$P_{X\ bio\ org\ VSS}$ is the volatile heterotrophic biomass removed in g/d

Q_A is the average daily flow in m^3

Y_H is the maximum heterotrophic biomass yield in g VSS/g BOD

f_d is the fraction of biomass as cell debris in g VSS/g VSS (see Table 3)

b_H is the endogenous decay rate coefficient for heterotrophic organisms in g VSS/g VSS•d (see Table 3)

SRT_{ORG} is the solids retention time in the organic reactor(s) in days

The maximum heterotrophic biomass yield (**Y_H**) is converted to a BOD basis using:

$$Y_H = 0.45\text{g VSS/g bCOD} * (1.6\text{g bCOD/g BOD}) = 0.72\text{g VSS/g BOD}$$

The amount of ammonia available for nitrification (NH$_0$), in g/m^3 or mg/L, can then be calculated by subtracting the amount of nitrogen consumed in the biomass from the influent TKN value:

$$NH_0 = TKN_i - N_e - 0.12\text{g N/g biomass} * P_{X\ bio\ org}$$

If a pre-anoxic reactor is used, the blended nitrate converted to nitrogen gas can also be subtracted using the following equation:

$$NH_0 = TKN_i - (NO_3\text{-}N_{blend} * \%Removal_{Pre\text{-}A}) - 0.12\text{g N/g biomass} * P_{X\ bio\ org},\ \text{g/m}^3 \text{ or mg/L}$$

MBBR Reactor Calculations, cont.

Calculations for Nitrification Stages

SALR is calculated in the nitrification stages, unlike in the organic stages where SALR selection is based upon the purpose of the reactor stage. For a single-stage nitrification system, the flux rate is based on the ammonia-limited flux rate. To determine this rate in g N/m²•d, use equation 9-48 from page 1022 of Metcalf (2014). Growth coefficient values are provided in Table 3 of this document.

$$J_{N2,15} = [NH_{3e} / (2.2\text{g/m}^3 + NH_{3e}) * 3.3\text{g N/m}^2\bullet\text{d}]$$

with NH_{3e} being the target ammonia level, typically 0.7mg/L or g/m³.

Using 0.7g/m³ for NH_{3e}, this calculates to:

$$J_{N2,15} = [0.7\text{g/m}^3 / (2.2\text{g/m}^3 + 0.7\text{g/m}^3) * 3.3\text{g N/m}^2\bullet\text{d}] = 0.797\text{g N/m}^2\bullet\text{d}$$

This value in g N/m²•d is then adjusted for temperature using:

$$J_{N2,Td} = (0.797\text{g N/m}^2\bullet\text{d}) * (1.098)(T_d\text{-}15)$$

For a two-stage nitrification reactor, the first stage flux rate is determined using the DO limited flux rate, calculated as follows at 15ºC:

$$J_{N1,15} = 1.07\text{g N/m}^2\bullet\text{d}$$

And it is calculated as follows at T_d:

$$J_{N1,d} = J_{N,15} * \Theta_{\text{DO LIMITED}}^{(Td-15)}, \text{ g N/m}^2 \text{ with } \Theta_{\text{DO LIMITED}} = 1.058$$

The second stage SALR is then determined using the ammonia limited flux rate as shown above. This value shall not be greater than 1.4g NH_3/m²•d (0.033lbs NH_3/ft²•d). One common design philosophy for nitrification is to design both nitrification reactors with equal area and volumes ($\mathbf{A_{N1} = A_{N2}}$).

Therefore, to calculate the ammonia available, in mg/L, in the second-stage nitrification reactor:

$$NH_{3N2} = [(J_{N2} * NH_0) + (J_{N1} * NH_e)] / (J_{N1} + J_{N2})$$

These values are converted to mass in order to size the denitrification reactors. For a single-stage nitrification system, J_{N2} is used for the SALR. The removal rate (**%Removal**) is calculated by:

$$\%Removal_{N1} = 1 - NH_{3e} / TKN_i$$

For a two-stage nitrification system, J_{N1} is used for the SALR. The removal rate for the first stage is then determined after the calculation above for ammonia in the second stage. Therefore, percent removal in the first stage is equal to:

$$\%Removal_{N1} = (NH_0 - NH_{3N2}) / NH_0$$

Removal rate for the second stage is then determined using:

$$\%Removal_{N2} = (NH_{3N2} - NH_{3e}) / NH_{3N2}$$

Nitrate Calculations for Post-Anoxic Denitrification

In order to determine the size of the post-anoxic stage, the nitrate converted from ammonia in the nitrification stages needs to be determined, in g/d, as well as any nitrate not consumed in the pre-anoxic stage, if used:

$$TKN_{\text{nconv Pre-A}} = NO_{3\text{-Nblend-M}} * (1 - \%Removal_{\text{Pre-A}})$$

$$TKN_{\text{conv NS1}} = NH_0 * \%Removal_{N1}, \text{ g/d}$$

$$TKN_{\text{conv NS2}} = (NH_0 - TKN_{\text{conv NS1}}) * \%Removal_{N2}$$

$$NO_3\text{-}N_{\text{Post-Ai-C}} = TKN_{\text{conv NS1}} + TKN_{\text{conv NS2}} + TKN_{\text{nconv Pre-A}}$$

MBBR Reactor Calculations, cont.

Determining Process-Generated Solids

Several calculations may apply for determining solids generated in the MBBR process(es), in kg. The complete solids analysis is performed using the five equations provided below.

Heterotrophic biomass ($\mathbf{P_{x\ hetero\ bio\ TSS}}$) is determined using:

$$P_{x\ hetero\ bio\ TSS} = Q_A * Y_H * (S_o - S_e) * (1kg/1000g) / [(0.85g\ VSS/g\ TSS) * (1 + b_{H,Td} * SRT_{org})]$$

Cell debris ($\mathbf{P_{x\ cell\ debris\ TSS}}$) is determined using:

$$P_{x\ cell\ debris\ TSS} = Q_A * Y_H * (S_o - S_e) * (1kg/1000\ g) * (f_d * b_{H,Td} * SRT_{org}) / [(0.85g\ VSS/g\ TSS) * (1 + b_{H,Td} * SRT_{org})]$$

Nitrifier biomass ($\mathbf{P_{x\ nitri\ biomass}}$), if nitrification is used, is determined using:

$$P_{x\ nitri\ biomass} = [Q_A * Y_N * NO_x * (1kg/1000g)] / [(0.85g\ VSS/g\ TSS)] * (1 + b_{N,Td} * SRT_N)]$$

Non-biodegradable VSS ($\mathbf{P_{x\ nbVSS}}$) is determined using:

$$P_{x\ nbVSS} = Q_A * nbVSS * (1kg/1000g)$$

Influent inert TSS ($\mathbf{P_{x\ inTSS}}$) is determined using:

$$P_{x\ inTSS} = Q_A * (TSS_i - VSS_i) * (1kg/1000g)$$

where

Q_A *is the average daily design flow in* m^3 *or liters*

Y_H *is the maximum heterotrophic biomass yield in either g VSS/g bCOD or g VSS/g cBOD (see Table 3)*

Y_N *is the maximum nitrogenous biomass yield in g VSS/g* NH_4 *(see Table 4)*

S_o *is the treated amount of cBOD or bCOD in mg/L, and typically assumed to be equal to the influent* BOD_5

S_e *is the effluent cBOD or bCOD in mg/L (see below)*

f_d *is the fraction of biomass that remains as cell debris in g VSS/g VSS (see Table 3)*

b_H *is the endogenous decay rate coefficient, adjusted for temperature in g VSS/g VSS•d (see "Estimating Pre-Anoxic Stage Values")*

b_N *is the endogenous decay rate for nitrifying organisms, adjusted for temperature in g VSS/g VSS•d (see Table 4)*

SRT_{org} *is the solids retention time or mean cell retention time in the organic stages, typically 4-6 days*

SRT_N *is the solids retention time or mean cell retention time in the nitrification stages, typically 4-6 days*

NO_x *is the concentration of nitrogen oxidized in mg/L (see "Determining Air Requirements for Treatment Processes")*

nbVSS is the non-biodegradable volatile suspended solids in mg/L

S_e is calculated in mg/L using:

$$S_e = K_s * (1 + b_{H,Td} * SRT_{org}) / [(\mu_{m,T} - b_{H,Td}) * SRT_{org} - 1],\ \text{mg/L}$$

where

K_s *is the temperature adjusted coefficient in mg/L (see Table 3)*

$\mu_{m,T}$ *is the maximum heterotrophic specific growth rate in g VSS /g VSS•d (see Table 3)*

b_H *is the endogenous decay rate coefficient for heterotrophic organisms in g VSS /g VSS•d (see "Estimating Pre-Anoxic Stage Values")*

S_e *is a small value compared to* S_o*; common practice assumes* $S_e = 0$

See the "Influent Waste Strength Calculations and Conversions" section for VSS, bpCOD, nbVSS, and pCOD calculations.

Aeration Requirement Calculations

Aeration is used for oxygen delivery to the treatment reactors and for mixing of the vessel. Both of these requirements should be calculated for each reactor, and the air delivery system sized to ensure adequate air is available.

Determining Air Requirements for Treatment Processes

Oxygen is required for the organic removal and nitrification reactors. The ability to transfer oxygen from the air into the process waste stream is dependent on several conditions, including elevation, temperature, depth of the air piping, and the size of the air bubble delivered. The mass of oxygen required is determined by the mass of contaminant being treated in conjunction with these factors. To determine these values, use the aeration coefficients in Table 5.

Table 5. Aeration Coefficients

Parameter	Typical	Range
Correction for mixing intensity and tank configuration, α_{ORG} =	0.8	0.3-1.2
Correction for mixing intensity and tank configuration, α_{NIT} =	0.7	0.3-1.2
Fouling factor for diffused aerators, **F** =	0.9	0.65-0.90
Relative DO saturation to clean water, β =	0.95	0.7-0.98
Oxygen saturation concentration, $C_{s\ 20°\ 1\ atm}$ =	9.08mg/L	
Target process operating oxygen concentration, C_{LORG} =	3.0mg/L	2-3mg/L
Target process operating oxygen concentration, C_{LNIT} =	4.0mg/L	3-6mg/L
Temperature activity coefficient, Θ for k_d =	1.04	1.03-1.08
Mid-depth correction factor, d_e =	0.4	0.25-0.45
Atmospheric pressure, P_s =	33.9ft	
Empirical temperature correction factor, θ =	1.024	

Determine saturated DO at sea level ($C_{\infty 20}$), in mg/L:

$$C_{\infty 20} = C_{s\ 20°\ 1\ atm} * (1 + d_e * D_f / P_s)$$

where

$C_{s\ 20°\ 1\ atm}$ *is the oxygen saturation concentration at 20°C and 1 atmosphere in mg/L (see Table 5)*

d_e *is the mid-depth correction factor, unitless (see Table 5)*

D_f *is the diffuser depth and determined using* $D_f = D_{REACT - 1\ foot}$, *in feet (see Table 1)*

P_s *is the atmospheric pressure in feet (see Table 5)*

Determine the adjusted temperature saturation for design ($C_{s,Tdesign}$), summer ($C_{s,Tsummer}$), or winter ($C_{s,Twinter}$) using Table 6.

Table 6. Adjusted Temperature Saturation

Temp.,°C	DO, mg/L	Temp.,°C	DO, mg/L	Temp.,°C	DO, mg/L	Temp.,°C	DO, mg/L
1	14.20	11	11.02	21	8.90	31	7.41
2	13.81	12	10.77	22	8.73	32	7.29
3	13.45	13	10.53	23	8.56	33	7.17
4	13.09	14	10.29	24	8.40	34	7.05
5	12.76	15	10.07	25	8.24	35	6.93
6	12.44	16	9.86	26	8.09	36	6.82
7	12.13	17	9.65	27	7.95	37	6.72
8	11.83	18	9.45	28	7.81	38	6.61
9	11.55	19	9.26	29	7.67	39	6.51
10	11.28	20	9.08	30	7.54	40	6.41

Aeration Requirement Calculations, cont.

Determine the unitless adjusted temperature saturation for design (τ_{design}), (τ_{summer}), and winter (τ_{winter}), using the following calculations:

$$\tau_{design} = C_{s,Tdesign} / C_{s\ 20°\ 1\ atm}$$

$$\tau_{summer} = C_{s,Tsummer} / C_{s\ 20°\ 1\ atm}$$

$$\tau_{winter} = C_{s,Twinter} / C_{s\ 20°\ 1\ atm}$$

Determine the unitless atmospheric pressure change with elevation and temperature for design, summer, and winter temperatures using the following equation from Appendix B on page 1910 of Metcalf (2014):

$$\Omega = P_b / P_s = \exp\ [-g * M * (z_b - z_s\ ) / (R * T_d)]$$

where

P_b *is the barometric pressure at the site, in meters*

P_s *is the standard barometric pressure of 1 atm (10.33m or 14.7psi)*

g is the acceleration due to gravity or $9.81 m/s^2$

M is the mass of a mole of air or 28.97kg/kg-mole

z_b *is altitude (site elevation), in meters*

z_s *is the pressure change from sea level (therefore, equals 0)*

R is the universal gas constant or 8314 N•m/kg-mole•K

T_d *is the temperature in Kelvin or 273.15 +°C*

gM/R = 0.03418 constant using SI units

Therefore:

$$\Omega_{DESIGN} = P_b / P_s = \exp\ [-0.03418 * z_b / (273.15 + T_{DESIGN})]$$

$$\Omega_{SUMMER} = P_b / P_s = \exp\ [-0.03418 * z_b / (273.15 + T_{SUMMER})]$$

$$\Omega_{WINTER} = P_b / P_s = \exp\ [-0.03418 * z_b / (273.15 + T_{WINTER})]$$

Determine the oxygen demand for the heterotrophic (organic removal) processes ($R_{o\ H}$) with the following calculation:

$$R_{o\ H} = Q_A * (S_o - S_e) - 1.42 * P_{x\ bio\ org\ TSS},\ g/hr$$

where

Q_A *is the average day design flow in* m^3

S_o *is the influent bCOD for the reactor in grams*

S_e *is the effluent bCOD for the reactor in grams*

$(S_o - S_e)$ *can be calculated using the influent mass of bCOD into a reactor multiplied by the removal rate*

$P_{x\ bio\ org\ TSS}$ *is the heterotrophic biomass and cell debris in g/day*

See the "Determining Ammonia Available for Nitrification" or "Determining Process-Generated Solids" sections and convert $P_{x\ bio\ org\ TSS}$ to grams:

$$P_{x\ bio\ org\ TSS} = [(P_{X\ bio\ org\ VSS} / Q_A) * Q_A] / 0.85\ gVSS/gTSS$$

Determine the oxygen demand in g/hr for the nitrogenous (nitrification) processes:

$$R_{o\ N} = 4.57\ g\ O_2/g\ NO_x * NO_x * Q_A * (1d/\ 24h)$$

NO_X is the amount of ammonia nitrogen to be converted to nitrate nitrogen in mg/L, and is calculated using the following equation:

$$NO_X = NH_0 - NH_e$$

Aeration Requirement Calculations, cont.

Determine the oxygen transfer rates for the heterotrophic (organic removal) and nitrogenous (nitrification) processes at design temperature:

Determine **OTR_f** in kg O_2/hr:

$$OTR_f = \alpha * F * [(\tau_{design} * \beta * \Omega_{design} * C_{\infty 20} - C_L) / C_{\infty 20}] * \theta^{(Td-20)} * SOTR$$

Determine **$OTR_{f\ HETERO\text{-}D}$** in kg O_2/hr:

$$OTR_{f\ HETERO\text{-}D} = \alpha_{ORG} * F *[(\tau_{design} * \beta * \Omega_{design} * C_{\infty 20} - C_{LORG}) / C_{\infty 20}] * \theta^{(Td-20)} * SOTR$$

Determine **$OTR_{f\ NITRO\text{-}D}$** in kg O_2/hr:

$$OTR_{f\ NITRO\text{-}D} = \alpha_{NIT} * F * [(\tau_{design} * \beta * \Omega_{design} * C_{\infty 20} - C_{LNIT}) / C_{\infty 20}] * \theta^{(Td-20)} * SOTR$$

where

α_{ORG} *is the correction for mixing intensity and tank configuration, unitless (see Table 5)*
α_{NIT} *is the correction for mixing intensity and tank configuration, unitless (see Table 5)*
F is the fouling factor for diffused aerators, unitless (see Table 5)
τ_{design} *is the adjusted temperature saturation, unitless*
β *is the relative DO saturation to clean water, unitless (see Table 5)*
Ω_{design} *is the atmospheric pressure change for elevation and temperature, unitless*
$C_{\infty 20}$ *is the saturated dissolved oxygen at sea level in mg/L*
C_L *is the target dissolved oxygen concentration in the reactor in mg/L*
θ *is the empirical temperature correction factor, unitless*
T_d *is the design temperature of the wastewater*
SOTR is the oxygen transfer rate under standard conditions in kg O_2*/hr*

Since oxygen transfer efficiency is temperature sensitive, these equations should be performed using summer conditions to confirm that the blowers selected will be adequate for that period of time. Calculate OTR_f for the heterotrophic and nitrogenous processes using the anticipated summer wastewater temperature:

$$OTR_{f\ HETERO\text{-}S} = [\alpha_{ORG} * (\tau_{summer} * \beta * \Omega_{summer} * C_{\infty 20} - C_{LORG}) / C_{\infty 20}] * \theta^{(TS-20)} * SOTR, \text{ kg } O_2/\text{hr}$$

$$OTR_{f\ NITRO\text{-}S} = [\alpha_{NIT} * (\tau_{summer} * \beta * \Omega_{summer} * C_{\infty 20} - C_{LNIT}) / C_{\infty 20}] * \theta^{(TS-20)} * SOTR, \text{ kg } O_2/\text{hr}$$

Determine the oxygen requirement for the heterotrophic (organic removal) and nitrogenous (nitrification) processes at design temperature:

Determine **$OTR_{ORG\text{-}D}$** and convert g/hr to lbs/hr:

$$OTR_{ORG\text{-}D} = R_{O\ H} / OTR_{f\ HETERO\text{-}D}$$

Determine **$OTR_{NIT\text{-}D}$** and convert g/hr to lbs/hr:

$$OTR_{NIT\text{-}D} = R_{O\ N} / OTR_{f\ NITRO\text{-}D}$$

As in the previous set of equations, these calculations should also be run to confirm blower selections for summer operation capability:

Determine **$OTR_{ORG\text{-}S}$** and convert g/hr to lbs/hr:

$$OTR_{ORG\text{-}S} = R_{O\ H} / OTR_{f\ HETERO\text{-}S}$$

Determine **$OTR_{NIT\text{-}S}$** and convert g/hr to lbs/hr:

$$OTR_{NIT\text{-}S} = R_{O\ N} / OTR_{f\ NITRO\text{-}S}$$

Aeration Requirement Calculations, cont.

Determine the air delivery requirements, in cubic feet per minute (cfm) at design temperature, for treatment in the organic ($\mathbf{AIR_{ORG}}$) and nitrification ($\mathbf{AIR_{NIT}}$) chambers:

$$AIR_{ORG\text{-}D} = OTR_{ORG\text{-}D} / [W_{AIR} * D_f * O_{2\ \%MM} * (60min/hr) * OTE_f]$$

where

$OTR_{ORG\text{-}D}$ *is the oxygen requirement for heterotrophic processes at design temperature in lbs/hr*

W_{AIR} *is the weight of air or 0.0753lb/ft*^{3}

D_f *is the diffuser depth in feet*

$O_{2\ \%MM}$ *is the fraction by weight of oxygen in air or 0.232lb* O_2*/lb air*

OTE_f *is the aerated oxygen transfer efficiency in %/ft*

$\mathbf{AIR_{NIT\text{-}D} = OTR_{NIT\text{-}D} / [W_{AIR} * O_{2\ \%MM} * (60\ min/hr) * D_f * OTE_f]}$, cubic feet per minute (cfm)

where

$OTR_{NIT\text{-}D}$ *is the oxygen requirement for nitrogenous processes at design temperature in lbs/hr*

W_{AIR} *is the weight of air or 0.0753lb/ft*^{3}

$O_{2\ \%MM}$ *is the fraction by weight of oxygen in air or 0.232lb* O_2*/lb air*

D_f *is the diffuser depth in feet*

OTE_f *is the aerated oxygen transfer efficiency in %/ft*

OTE_f is dependent on the selected method of aeration and air bubble size. Coarse air is typically considered to have an OTE of 0.9% efficient per foot of depth (approx. 3% efficient per meter of depth), while the OTE of fine-bubble aeration is typically around 2.0% efficient per foot of depth (approx. 6.5% efficient per meter of depth). The depth is measured from where the bubble is created and the liquid elevation in the vessel.

Determine the air delivery requirements in CFM for treatment for the AIR_{ORG} and AIR_{NIT} chambers at summer temperature:

$$AIR_{ORG\text{-}S} = OTR_{ORG\text{-}S} / [W_{AIR} * O_{2\ \%MM} * (60\ min/hr) * D_f * OTE_f]$$

$$AIR_{NIT\text{-}s} = OTR_{NIT\text{-}s} / [W_{AIR} * O_{2\ \%MM} * (60\ min/hr) * D_f * OTE_f]$$

In systems with multiple reactors, these calculations are performed separately for each reactor. Contact Orenco for examples.

Determining Air Requirements for Mixing of Aerated Reactors

In addition to the oxygen necessary for the treatment process inside the aerated reactors, the air required for carrier mixing must be calculated. In low waste-strength applications, mixing air is often the parameter that controls blower sizing. To determine the air required for mixing in each aerated reactor, the coefficient of mixing air flow ($\mathbf{C_{MIX}}$) is 35scfm per 1000ft^3 of volume. The calculation for mixing in each reactor, in CFM, is:

$$MIX_{AER} = C_{MIX} * D_{REACT} * A_{REACT}$$

where

D_{REACT} *is the liquid depth in the reactor, in feet*

A_{REACT} *is the area of the reactor, in feet*

Design Notes and Special Considerations

It is important that the mixing air calculation be repeated if vessel dimensions are changed from the original calculated values during the design process. For example, if a system was designed for a vessel width of 10ft and length of 7ft but the length was changed during the design process to be 10ft long, the mixing air required will be 43% greater.

Aeration Requirement Calculations, cont.

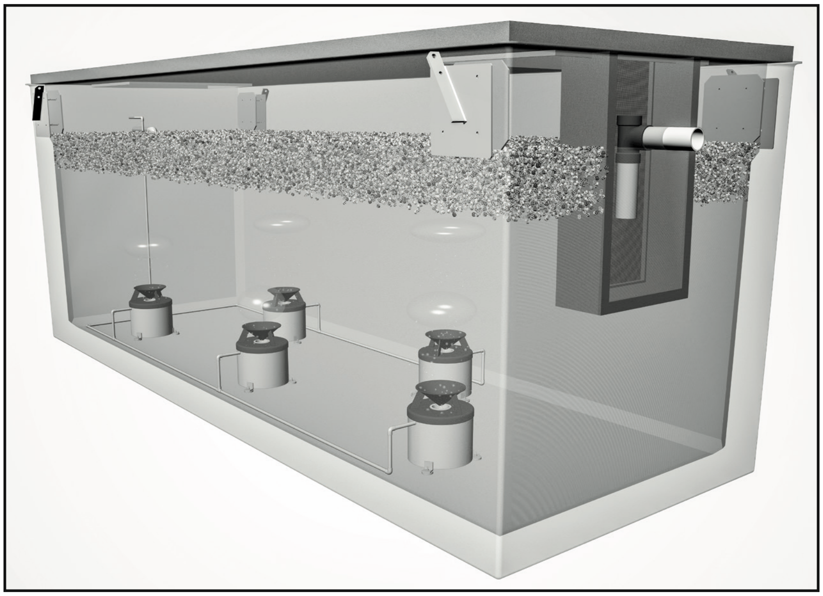


Figure 12. Typical Pneumatic Ejector Configuration for Orenco Systems MBBRs

Determining Air Requirements for Mixing of Anoxic Reactors

Pre- and Post-Anoxic Mixing: Pneumatic Ejectors

With no moving parts to fail and significant savings in energy cost, pneumatic ejectors provide a substantial benefit over traditional submersible mechanical mixers. The concept is simple – create a large bubble at the bottom of the chamber that will travel upward to the surface. This large bubble displaces water and stirs the media, shearing excess biofilm from the carriers. The ejectors have no moving parts and only require a small-diameter air feed line to each unit. Figure 12 shows a typical system layout. The staggered ejector configuration helps to ensure better mixing inside the reactor.

The number of ejectors required can actually be fewer for a deep tank than for a shallow tank because of the additional upward travel distance. Table 7 provides guidance in determining the number of ejectors necessary to provide proper mixing inside the anoxic reactors.

Table 7. Minimum Pneumatic Ejector Requirement Based on Vessel and Media Fill

Vessel	Area per Ejector (A_{EJECT}), Up to 20% Fill	Area per Ejector (A_{EJECT}), Greater than 20% Fill
MBBR08	28ft^2 (2.6m^2)	20ft^2 (1.9m^2)
MBBR10	40ft^2 (3.7m^2)	28ft^2 (2.6m^2)
MBBR12	45ft^2 (4.2m^2)	30ft^2 (2.8m^2)

The number of ejectors required for the pre-anoxic and post-anoxic reactors is calculated using:

$$\#\ \text{Ejectors}_{PRE\text{-}A} = \text{Reactor Area}_{PRE\text{-}A} / A_{EJECT}$$

$$\#\ \text{Ejectors}_{POST\text{-}A} = \text{Reactor Area}_{POST\text{-}A} / A_{EJECT}$$

Unlike most mechanical mixers, pneumatic ejectors are only pressurized for a few minutes every 1-4hrs. Table 8 provides a guideline for cycling the pneumatic ejectors, based on percent of media fill.

Table 8. Cycle Time for Pneumatic Ejector Operation

Percent Media Fill	Cycle Time	Cycle Frequency
10%	3-5 minutes	Once per 4hrs
20%	3-5 minutes	Once per 3hrs
30%	3-5 minutes	Once per 2hrs
40%	3-5 minutes	Once per hour
Greater than 40%	5-10 minutes	Once per hour

During this period, each ejector requires approximately 5cfm to release one or two bubbles, which mix the contents of the chamber and shear excess biofilm from the carriers. Determining the air feed system, in CFM, for the pre-anoxic and post anoxic reactors is simple:

$$\text{Air}_{PRE\text{-}A} = \#\ \text{Ejectors}_{PRE\text{-}A} * 5\text{cfm/ejector}$$

$$\text{Air}_{POST\text{-}A} = \#\ \text{Ejectors}_{POST\text{-}A} * 5\text{cfm/ejector}$$

The air feed for the pre-anoxic and post-anoxic reactors can be provided by a dedicated blower, or air can be fed using the organic and/or nitrification feed blowers by using an electrically actuated valve, set up to operate on a timer (cycle times are outlined in Table 8).

Aeration Requirement Calculations, cont.

Pre- and Post-Anoxic Mixing: Mechanical Mixers

Mechanical mixers can be used for mixing contents and shearing excess biofilm from the carriers in the pre- and post-anoxic reactors. Mixing is typically provided by submersible mechanical mixers with large, propeller-like blades that are set to run at very low revolutions per minute (rpm). Most commonly, these mixers are in continuous operation. Carriers tend to float when not being mixed, so mixers should be mounted near the surface with a slight negative inclination to push the media downward. Mixers should not be located too close to the surface, in order to avoid entraining air and pulling it into the anoxic vessel(s). Typically, mixers require between 25 and 35W/m^3 to mobilize the floating bed of media (WEF 2010, chap. 5 sec. 3.2). Mixing energy is calculated in watts, using:

$$\text{Mixing Energy}_{\text{PRE-A}} = \text{Volume}_{\text{PRE-A}} * 35\text{W/m}^3$$

$$\text{Mixing Energy}_{\text{POST-A}} = \text{Volume}_{\text{POST-A}} * 35\text{W/m}^3$$

Supplemental Chemicals

Almost every configuration of MBBR requires or benefits from supplemental chemicals. Alkalinity addition for buffering the nitrification process, carbon addition for denitrification, and polymer addition to aid in solids settling are the most common and are covered below.

Alkalinity Requirements

Ensuring that the pH remains above 7.5 (minimum pH of 7) at all times is essential for the nitrification process. Supplemental alkalinity (**A_T**) should be included if influent alkalinity (**$A_{T\text{-IN}}$**) is insufficient to buffer the process. During nitrification, 7.14mg/L alkalinity is used per 1mg/L TKN; during denitrification with a pre-anoxic return loop (at 100% denitrification), half of that – or 3.57mg/L – is returned. To be conservative when calculating the alkalinity need (**$A_{T\text{-NEED}}$**), assume a 60% denitrification efficiency in the pre-anoxic system, returning 2.14 mg/L of alkalinity (**$A_{T\text{-RETURN}}$**). Without a pre-anoxic component, there is no return and $A_{T\text{-RETURN}}$ is equal to zero (0). Use the following equation to determine demand (**$A_{T\text{-DEMAND}}$**) in mg/L:

$$A_{T\text{-DEMAND}} = \text{TKN}_i * (7.14\text{mg/L } A_T - A_{T\text{-RETURN}}) / 1\text{mg/L TKN}), \text{ mg/L}$$

Use the following equations to calculate $A_{T\text{-NEED}}$ in mg/L, assuming complete nitrification of the denitrified effluent:

$$A_{T\text{-NEED}} = A_{T\text{-RESIDUAL}} + A_{T\text{-DEMAND}} - A_{T\text{-IN}}$$

$$A_{T\text{-NEED}} = 100\text{mg/L} + A_{T\text{-DEMAND}} - A_{T\text{-IN}}$$

The target residual for alkalinity (**$A_{T\text{-RESIDUAL}}$**) is 100mg/L. (See the “Nitrification Treatment” section for more information.) If the result of the equation above is a positive value, the system will require supplemental alkalinity addition. If the result is a negative value, there is likely a surplus of alkalinity in the source water, and the system should function without alkalinity addition.

Carbon Addition

Carbon addition is always required for the post-anoxic reactor and may be beneficial in the pre-anoxic reactor as well. The carbon source should be easily biodegradable in order to properly denitrify. Natural waste streams are not as predictable or biodegradable as supplemental added carbon. Therefore, in the pre-anoxic reactor, the SALR is typically tied to the source of carbon. A more aggressive SALR is used with supplemental carbon addition. (See the “Pre-Anoxic Treatment”section for more information). Temperature and choice of chemical have a significant effect on denitrification. (See the “Post-Anoxic Treatment” section and Figure 11, in particular, for more information.)

Pre-Anoxic Reactor

Proper denitrification requires a minimum C:N ratio of 4:1. The blend nitrate concentration and mass (**$NO_3\text{-}N_{\text{RNOX-M}}$**) were determined in “Estimating Pre-Anoxic Stage Values” from the “MBBR Reactor Calculations” section of these guidelines, and BOD_{5i} is either known or estimated. Use the following equation to determine the unitless C:N ratio:

$$\text{C:N}_{\text{PRE-A}} = \text{BOD}_{5i} / NO_3\text{-}N_{\text{RNOX-M}}$$

Additional pre-anoxic carbon is required if this value is less than four (4). If this value is greater than four (4), the initial influent waste stream should be sufficient to support denitrification, though SALR rates should be reduced as discussed in the “Pre-Anoxic Treatment” section of these guidelines.

Supplemental Chemicals, cont.

Post-Anoxic Reactor

Post-anoxic reactors always require carbon addition. The amount of carbon needed is based on the amount of nitrate available for denitrification. Determine the carbon (**$CARB_{SUPP-M}$**) needed, in kg or lbs, using the value for nitrate by mass (**$NO_3\text{-}N_{Post-Ai-M}$**) as shown in the "Nitrate Calculations for Post-Anoxic Denitrification" section:

$$CARB_{SUPP-M} = NO_3\text{-}N_{Post-Ai-M} * C{:}N_{POST-A}$$

The C:N ratio for the post-anoxic reactor is selected by the system designer and can range from 4-8, with 4.5-5 typically being used. If the value used is too high, excess carbon in the form of BOD will be passed through the system, requiring a polishing stage for removal to meet permit limits with low BOD_5 or $cBOD_5$ requirements.

There are many factors affecting denitrification that must all be evaluated, such as temperature, proper anoxic conditions present, and hydraulic retention time. Sufficient C:N ratio alone will not ensure complete or near complete denitrification. (See the "Process Stages – MBBR Treatment Systems" section for more information.)

Polymer or Other Chemical Addition

Other additives may also be considered, such as polymer to improve settling in the clarifier or chemicals to precipitate out phosphorous. These chemicals are typically added in the clarifier. Chemical selection and sizing are based on the overall system configuration and permit requirements. Designers should carefully evaluate options and include them when necessary or justified by savings in capital costs and/or operation.

Critical Equipment and Materials

Equipment selection is a critical aspect of the design of MBBR treatment systems. This section covers some of the most important equipment that affects the design or operation of an MBBR treatment system. There are several other ancillary components that are not critical to the design and operation which are not specifically covered in this document.

Media (Carrier) Selection

Media or carrier selection is vital to the design of the system. The surface area of the carriers is used when calculating reactor size. Surface area is typically listed with both an overall surface area and a protected surface area. The protected surface area does not come into direct contact with the other carriers while moving through the reactor. Many design equations do not differentiate between the two, as even the unprotected areas of the carriers will have a thin biofilm where biological treatment occurs. However, this unprotected biofilm is less stable since it is consistently contacting other carriers. A conservative design always uses the protected surface area when determining reactor vessel sizes.

Carriers come in several configurations with the cylindrical "honeycomb" design being the most common. Carriers may also be oval or trapezoidal in shape, with significant surface area within the oval or trapezoid. Though there is little research comparing the various configurations, the honeycomb design has a long history of successful use in projects. With the more "open" design, it has been demonstrated that proper mixing will dislodge excess biofilm, keeping an efficient thin biofilm in place for biological treatment to occur. Most honeycomb carriers have a surface area that ranges from 400-600m^2/m^3, and the wafer-like chip carriers may have surface areas up to 3000m^2/m^3. Media with much lower surface area and more open space are available for waste streams that may contain more grease and oil, allowing for easier sloughing of grease buildup on the carriers.

Obviously, the greater the surface area (and preferably the protected surface area), the less space is required for treatment. Reactor size is directly proportional to the surface area of the carrier. (See the "MBBR Reactor Sizing and Hydraulic Retention Time" section.) Additionally, HRT in the reactor is a function of the overall volume available for liquid, so the less space taken up by the carriers, the greater the reactor HRT. In Orenco MBBRs, a honeycomb-style media with a bulk specific area of 650m^2/m^3 and a protected surface area of 550m^2/m^3 is typically used. This particular media is constructed from either first-use or recycled material, each with a different color. The two materials are typically used in a reactor together (≈ 80/20% mix) with the contrasting colors allowing for easy visual inspection of the mixing within the chamber.

Critical Equipment and Materials, cont.

Media Retention

Media retention within the reactors is important; maintaining retention with minimal operator involvement should be considered. Figure 13 shows the two primary forms of media retention: (a) vertical plates or screens and (b) horizontal sieves. Note that the vertical plate example is for an anoxic chamber, requiring an air sparge system to keep the screens from developing a biofilm and potentially plugging. In smaller systems, vertical perforated plates can be used for media retention. These plates have larger orifices than screens, minimizing plugging; however, access to the plates is required for inspection and maintenance, if necessary.

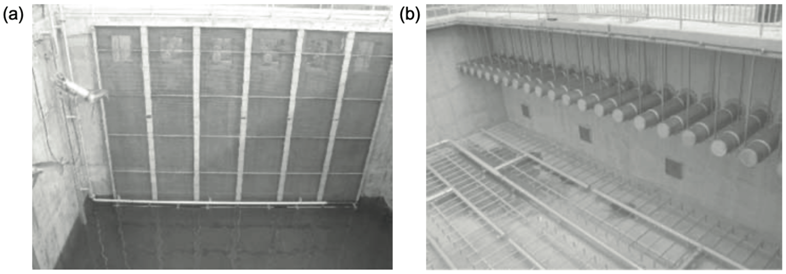


Figure 13. Media Retention Examples
(Reprinted from WEF 2010, chap. 5 sec. 2.0)

Oxygen Delivery System

Delivering air to microbes submerged in wastewater is inherently inefficient. Coupled with the need for mixing (either by air delivery or supplemental mechanical mixing), the method of delivering oxygen to the biofilm becomes one of the most critical elements of the overall MBBR design. As discussed briefly in the “Determining Air Requirements for Treatment Processes ” section, the efficiency of oxygen transfer is dependent on bubble size.

Coarse air has been the most commonly used method for delivery of oxygen – a simple system consisting of a network of pipes with drilled or tapped orifices. It is moderately effective for mixing but has an oxygen transfer efficiency (OTE) of only around 0.9% per foot of depth or 9% efficiency (a 91% waste of energy) in a basin with 10ft of orifice submergence.

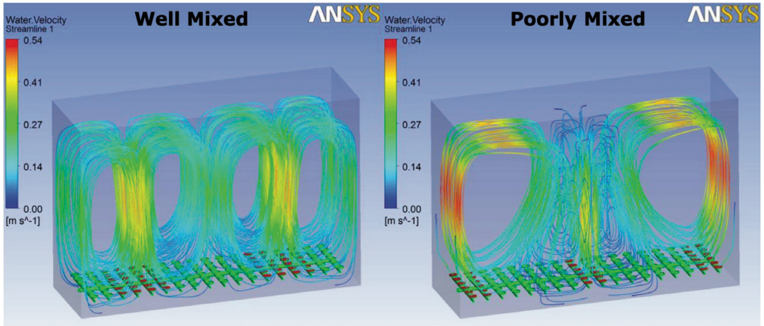


Figure 14. Mixing with Fine-Bubble Diffusers
(Reprinted from Degrémont 2011)

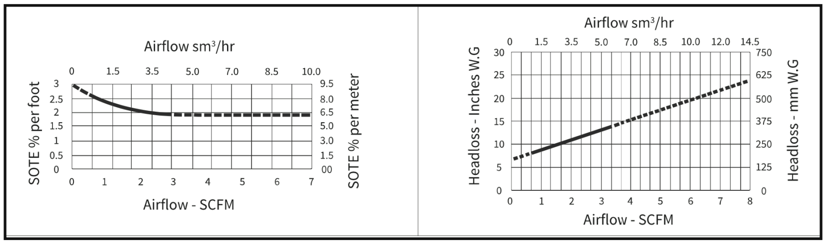


Figure 15. Fine-Bubble Diffuser SOTE and Headloss Chart
(Reprinted from SSI, 9" Fine Bubble Disc Diffusers)

Fine-bubble diffusers provide an OTE of around 2% per foot of depth or 20% efficiency (an 80% waste of energy, but a 222% increase in efficiency over coarse air) in a basin with 10ft of orifice submergence. Fine-bubble diffusers need less than half the electricity and significantly smaller components to generate and deliver air compared to coarse air. The drawback of fine-bubble diffusers is the complexity of the piping network and difficulty of adequately mixing the reactor contents. However, a study presented in 2011 by Degrémont Technologies and Suez Environnement has led to spacing strategies using fine-bubble diffusers that demonstrate excellent mixing capability (see Figure 14). Thus, fine-bubble diffusers can provide a significant savings in long-term operational cost.

Fine-bubble diffusers are most often provided as discs or flat plates. When selecting a fine-bubble diffuser, the key parameters are standard oxygen transfer efficiency (SOTE) and headloss. Figure 15 shows a typical set of curves developed by the manufacturer for each model of diffuser. The solid line on each chart indicates the most efficient operating range, in this case between 0.7 and 3cfm (0.75-4.25m^3/hr). These charts will help determine the number of diffusers or diffuser arrays necessary to provide the appropriate amount of oxygen and mixing air to the aerated reactors. Use the expression below to determine the quantity of diffusers:

$$\#\text{Diffusers} = \text{AIR} / (\text{QDIFF}_{\text{AIR}} * \text{PF}_{\text{DIFF}})$$

where

AIR is the critical air requirement (process or mixing) for the reactor at design temperature in cfm

$\text{QDIFF}_{\text{AIR}}$ *is selected flow value of diffuser model used*

PF_{DIFF} *is performance factor for future diffuser wear, typically 0.9*

Critical Equipment and Materials, cont.

Blower Selection and Configuration

Blower selection is critical to designing MBBR treatment systems. Nearly all of the energy at an MBBR treatment plant is used to generate and move air to the treatment processes, so efficiency is paramount. The system must have reliable air delivery for both treatment and mixing, so developing a strategy to ensure air delivery is important. Orenco MBBRs use either regenerative (also known as side channel) or kinetic blowers and non-contacting impellers. Regenerative and kinetic blowers are quieter than centrifugal blowers and require less maintenance due to their non-contacting impeller configuration.

Before selecting a blower, determine how to deliver air to the system. If air delivery to the organic removal reactors and nitrification reactors is located nearby, a good design strategy is to use a three-blower system, with each blower sized to deliver 50% of the air needed. In this scenario, two blowers run simultaneously. After a period of time (typically 24hrs), they shut off, and a second set of two begin to run. For example, blowers 1 and 2 run, then 1 and 3, then 2 and 3, and the cycle repeats. If one blower fails, a sensor will bring on the third blower, and full aeration continues until the operator repairs or replaces the failed blower. Each blower needs an isolation valve and a pressure relief valve. See “Valving and Air Flow Measurement” in this section of these guidelines for information on ensuring proper air flow to each reactor.

Nitrification typically takes more air than organic removal. In systems with large differences in air requirements, it may be sensible to use separate blowers for each process. In this scenario, there would be two blowers for organic removal, each capable of delivering the appropriate amount of air to the process (100% of the air needed), alternating with another blower after a period of time. The same concept would be used for the nitrification process.

Air is also necessary for mixing of the pre-anoxic reactor and the post-anoxic reactor. This is provided either by a dedicated set of alternating blowers or by the use of an electrically actuated valve. For guidelines on how often this valve should open, see Table 8 in the “Determining Air Requirements for Mixing of Anoxic Reactors” section. As shown in Table 8, anoxic reactors with greater than 30% fill require cycles more frequent than every 2hrs, in which case separate blowers are highly recommended.

In all of these scenarios, the operator should specify and keep in stock a spare blower of each model used.

Variable Frequency Drives (VFDs)

The key to energy conservation in MBBR systems is to size blowers appropriately and adjust air flow with VFDs. This allows the system to operate at the lowest possible air delivery rate for achieving effective treatment and mixing. Too little or too much DO can have adverse effects on the processes. Undesirable organisms prosper in conditions where DO is too low or too high; beneficial organisms do not perform twice as well if they are supplied with twice the DO they require. Too high a DO can also adversely impact settling.

Once the air flow requirements are established as shown in the “Aeration Requirement Calculations” section, look for a blower or set of blowers that are close to the design point. In an MBBR system, where blowers are operating 24hrs per day, using a blower with more horsepower than needed will unnecessarily increase energy costs. Even using VFDs to lower the cycles may have some limitations because most blower manufacturers establish minimum cycles for their units (45Hz is a common lower limit).

It is important to review the affinity laws for rotational speed (ω). Table 9 shows the three relationships that apply when rotational speed is changed.

Table 9. Affinity Laws for Rotational Speed

Parameter	Equation
Flow (Q) varies directly with the speed (ω)	$Q_2 / Q_1 = \omega_2 / \omega_1$
Head (H) varies with the square of the speed (ω)	$H_2 / H_1 = (\omega 2 / \omega 1)^2$
Brake horsepower (P) varies with the cube of the speed (ω)	$P_2 / P_1 = (\omega 2 / \omega 1)^3$

As rotational speed slows, power drops dramatically. For example, at a full rotational speed of 60Hz, the power used would be 100% of full load, but at 48 Hz (80% of full load), the power used would be:

$$P_2 = (\omega_2 / \omega_1)^3 / P_1 = (0.8 / 1)^3 / 1 = (0.8 * 0.8 * 0.8) = 0.51 \text{ or } 51\%$$

This equation shows that only 51% of the energy is used to accomplish 80% of the work. The benefit is greater for blowers than for pumps. With a pump, head drops as a square of speed – a significant issue. But with a blower, DO is determined by air flow, not pressure. The dynamic pressure is merely the result of the resistance to air flow; the static pressure is unchanged. Properly sized blowers coupled with the wise use of VFDs can provide significant energy cost savings.

Critical Equipment and Materials, cont.

Valving and Air Flow Measurement

Sufficient air flow to each reactor is essential for both biological treatment and mixing. Properly managing DO and air flow for mixing ensures that energy isn't wasted. Air flow to each reactor should be controlled with an adjustable valve. These valves are typically located close to the reactor so the operator can visually determine the effect of adjustment. Also, when a set of blowers is used for both organic removal and nitrification purposes, valves should be provided within the shelter that houses the MBBR to provide proper distribution of air to each of the processes.

The number of valves and air flow devices within the shelter is dependent on the system configuration, the size of the project, and the permit requirements. For very strict treatment parameters, the designer should consider valving and air flow measurement for each reactor. Separate valving and air flow measurement for the organic treatment process and nitrification processes are typically sufficient for less stringent treatment parameters. Air flow monitors are typically vane-style, spring-loaded meters. They can either be manually read analog meters, or they can be digital meters that provide for manual reading along with monitoring and logging through the system control panel. Thermal mass flow meters with temperature measurement can be used for highly sensitive measurements.

Sensors and Instrumentation

Instrumentation packages should be considered for use with an MBBR treatment system. Sensors can be used for informational purposes to assist the operator in making adjustments or changes. For more complex projects, they can be used to control the treatment process.

Dissolved Oxygen Sensors for Continuous Monitoring

DO sensors are relatively dependable and affordable and are worth consideration for real-time measurement of DO in the organic removal and nitrification processes. Operation control using DO sensors is typically needed only when there is a large variation in flow requiring frequent operator oversight of adjustments.

Ammonia and Nitrate Sensors for Continuous Monitoring

Ammonia and nitrate probes are usually membrane-based, requiring frequent – often weekly – maintenance and calibration. Due to anticipated maintenance requirements, these probes are typically used only on larger projects that employ full-time operators.

pH and ORP Sensors for Continuous Monitoring

Sensors used to measure pH and Oxygen Reduction Potential (ORP) are usually membrane-based, requiring frequent maintenance and calibration. There are many handheld testing devices that can provide the same information, so these sensors are not typically recommended.

Multiparameter Water Quality Meters for Monitoring as Needed

Portable multiparameter water quality meters are a sound investment for wastewater system operators. Devices such as the YSI ProDSS can hold up to four sensors for measuring multiple parameters, including pH/ORP, ammonium, nitrate, DO, and turbidity. These devices can be employed on a scheduled basis or used to check various reactors when troubleshooting. They are easily calibrated, cost effective, and simple to operate.

Basic Control System

The control system for most MBBR projects is fairly simple due to the minimum number of moving parts and motors. The most critical component in the control system is the remote telemetry unit, used for emergency communication, remote control, and data tracking. An Orenco TCOM™ ATRTU-NET remote telemetry unit gives facility managers, operators, and maintenance providers the ability to remotely monitor and control performance of mechanical equipment in real time.

VFDs, discussed in "Blower Selection and Configuration" in this section of these guidelines, can be located within the control system or mounted directly to the blowers. VFDs should be adjustable through the control system and directly at the unit itself. Remote access and adjustment is important for responding to changing operating conditions. Adjustment at the unit is simple, accomplished with a dial or push buttons.

For larger projects or complex projects with full-time operators, control integration with probes or sensors for automated operational adjustment can save significant money on electrical costs. This control logic is sophisticated and requires more operational attention to ensure sensors and probes are regularly calibrated and reading properly. It must also be set up to identify and address the potential for sensor malfunction or misreading.

Operational Parameters

There are several key operational parameters to be addressed with an MBBR treatment system, including configuration and control logic, start-up issues, and ongoing maintenance.

Peak Velocity

The expected peak velocity (flow rate divided by cross-sectional area of reactor) through an MBBR during high-flow conditions requires consideration. MBBR systems should be designed with a target velocity below 20m/h to ensure the carriers stay evenly distributed throughout the reactor. Above this velocity, media carriers tend to migrate and stack against the media retention sieves. Orenco MBBR vessels are configured to minimize this condition. If necessary, MBBR systems with extremely high flows should be designed as parallel treatment trains to reduce velocities.

Logic- and Sensor-Based Control Options

There are several logic- or sensor-based control options that can be used with an MBBR system; some of these are described below. The choice of options is highly dependent on system size, flow fluctuations, temperature, permit requirements, etc. Each project requires individual evaluation to determine which, if any, of these options are merited.

Influent Flow Meter

An influent flow meter is recommended whenever possible. Influent flow meters help identify high periodic flows into the system, which can then be addressed by using logic programming to adjust the blower rotational speed upward, if needed. Conversely, during very low periodic flow into the system, program logic can be used to reduce the rotational speed to the minimum speed required to achieve adequate mixing.

Clearing Diffusers During Blower Alternation

The rotational speed of the blower(s) is controlled by a VFD, is set according to expected influent values, and operates in a continuous run configuration. A short shutdown of the blower(s) occurs for a few minutes every day to relax the diffusers and to alternate the blowers. After the shutdown, the blower(s) will run at 100% speed for a few minutes to displace any buildup on the diffuser prior to returning to the programmed rotational speed value.

Using DO Sensors to Control Blower Rotational Speed

As mentioned in the “Sensors and Instrumentation” section, DO sensors can be used for controlling blower rotational speed(s). This is typically reserved for larger projects and those with high flow fluctuations. When this method is used, DO sensors must be checked regularly against other methods of DO measurement to ensure accuracy, and the sensors calibrated when necessary. When mixing air demand controls exceed the air demand required to meet the DO target, this method is not typically considered.

Using Nitrate/Ammonium Sensors to Control Blower Rotational Speed or to Trigger or Adjust a Recycle Loop

Per the “Sensors and Instrumentation” section, nitrate and ammonium sensors are typically used only on larger projects or those with highly restrictive permits. There are numerous parameters that affect nitrification (for example, temperature or alkalinity), so these sensors are usually used only as indicators, not for control. They can be used in conjunction with DO probes to control blower rotational speed within certain parameters, but a large increase in DO does not result in a large increase in nitrification. For highly restrictive permits, these sensors can be used to trigger a reject loop back to the front end of the plant (pre-anoxic or organic removal reactor), or to modify the existing rate of recycle back to the front end for plants with a recycle loop.

In-Field Operator Adjustments

MBBR treatment system processes are fairly stable. Typically, only a few adjustments are necessary in the field, and these are usually based on significant changes in the flow, influent waste strengths, or temperature.

Blower Rotational Speed and Valve Adjustment

Rotational speed of the blower(s) or valve adjustment will impact the amount of air delivered to the reactor(s). During periods of high flow, the VFD can be adjusted upward to increase rotational speed and deliver more oxygen to the process. During these adjustments, it is important to keep each reactor within its targeted DO range. (See the “Organic Treatment,” “Nitrification Treatment,” and “Blower Selection and Configuration” sections for details.) Variations in influent waste strength may also require adjustment of the VFD and valve position, especially for increases or decreases in specific parameters. For example, if the system sees a sharp increase in ammonia with little or no increase in BOD_5, it requires more air delivery to the nitrification reactor(s), but not to the organic removal reactors. A simple valving adjustment may suffice, but a combination of an increase in rotational speed and a closing down of the organic valve position to keep the DO in target range will likely be necessary.

Operational Parameters, cont.

Blower rotational speed can also be increased to assist in more aggressive mixing of the reactor(s) in the event that inadequate mixing has allowed too much growth on the carriers. This may only require a short-term aggressive mixing to shear excess growth. In the event that a long-term increase in air delivery is required, the DO should be measured to ensure it is kept within the desirable range. Conversely, blower rotational speed can be decreased in the event that the mixing is too vigorous to allow the carriers to develop a consistent thin biofilm for treatment.

Adjusting Pre-Anoxic Return Rate (Q_{RNOX})

Operators can adjust pre-anoxic return rate, Q_{RNOX},as needed. The need for adjustment may arise from several factors. Incomplete conversion of nitrogen in the pre-anoxic stage can occur when the DO level in the pre-anoxic tank is too high due to an overaggressive Q_{RNOX}. In this event, the operator would adjust the Q_{RNOX} rate down until the DO levels fall within the ranges described the “Pre-Anoxic Treatment” section of these guidelines. Conversely, Q_{RNOX} may be increased if complete conversion is occurring but there is still significant carbon available for additional conversion. Using incoming raw BOD in the influent will reduce the need for treatment in the organic treatment reactors (possibly allowing for a reduction of air flow) and reduce the amount of carbon added to the post-anoxic treatment stage, saving on chemical cost.

Adjusting Chemical Feed Rates

Alkalinity and carbon feed rates can be adjusted by the operator, if necessary. If nitrification is limited due to inadequate alkalinity, the feed rate can be adjusted upward. If the residual alkalinity significantly exceeds the recommended residual value (100mg/L), the feed rate can be adjusted downward to save on chemical costs. Similar adjustments can be made to the carbon feed (increasing the feed rate if incomplete denitrification occurs due to lack of BOD and decreasing the feed rate if complete denitrification occurs coupled with a high residual BOD). Polymer addition and other chemical additives can also be increased or decreased depending on performance.

Miscellaneous Information

Foaming

Foaming in MBBRs is uncommon but it can occur, especially during system startup. Short-term treatment performance may be diminished if a defoaming agent is necessary, as the defoamer coats the media and impedes diffusion to the biofilm. Do not use silica-compound defoaming agents – they are incompatible with the plastic media.

Access for Diffuser Maintenance and Replacement

The fine-bubble membrane air diffusers will eventually require maintenance or replacement. It is essential that any system design include the ability to access or remove the diffusers. In the event of a system shutdown for any prolonged period of time, the reactor should be drained while maintaining a minimum air flow to keep solids from settling onto and potentially clogging the diffuser membrane. The reactor should then be refilled with clean water for thermal protection against severe cold or hot temperatures.

Media Transfer

Media removal is rare in a well-designed and well-constructed MBBR. However, in the event that media removal becomes necessary, the contents of a reactor, including carriers, can be transferred using a 100mm (4in) recessed impeller pump. The media should be moved to a holding tank or vessel and kept wet, if possible, to preserve any biofilm while maintenance occurs.

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