*A SunCam online continuing education course*

# MBBR Wastewater Treatment Processes

by

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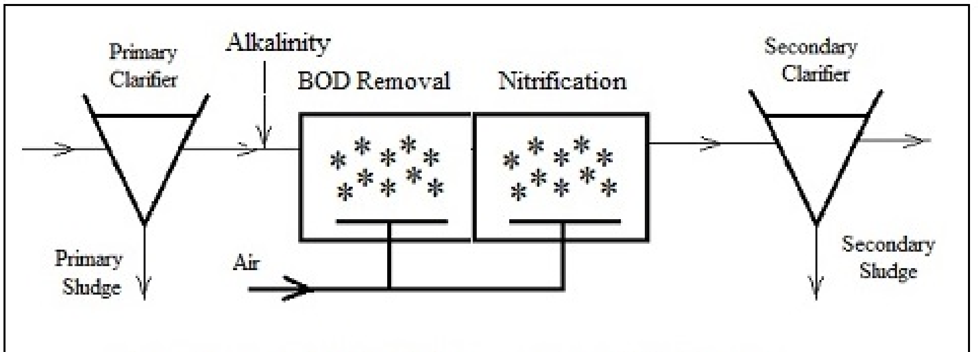
# 1. Introduction

The Moving Bed Biofilm Reactor (MBBR) wastewater treatment process is a relatively recent addition in the wastewater treatment field. It was developed in Norway in the 1980's and is now in use in many countries throughout the world. It is an attached growth process, but is similar to activated sludge in some ways also. It uses plastic carriers to provide a surface on which biofilm grows. The plastic carriers are kept suspended in the aeration tank by an aerator for an aerobic process or by mechanical mixing for an anoxic or anaerobic process. The plastic carriers are kept in the system by a sieve at the outlet of the tank. There is no need for sludge recycle in an MBBR process and the required reactor size is typically significantly smaller than for an activated sludge process treating the same wastewater flow, or for other common attached growth processes like the trickling filter or RBC. The MBBR process can be used for BOD removal, nitrification and/or denitrification. This course includes background information about the MBBR process and a description of a commonly used design approach, along with several worked examples illustrating the calculations.

A sample spreadsheet for making MBBR process design calculations is included with this course. Coverage of spreadsheet use for MBBR process design calculations is discussed in the course and illustrated with example calculations.




Two-Stage BOD/COD Removal and Nitrification

# 2. Learning Objectives

At the conclusion of this course, the student will

- Know the differences between attached growth and suspended growth biological wastewater treatment processes
- Be familiar with the general configuration and components of an MBBR wastewater treatment process
- Be able to name the six MBBR process configurations discussed in this course
- Be able to calculate the loading rate of a wastewater constituent to an MBBR process (in lb/day and g/day) for specified wastewater flow rate and constituent concentration
- Be able to calculate the required carrier surface area for an MBBR wastewater treatment process for specified SALR and loading rate
- Be able to calculate the required MBBR tank volume for specified carrier surface area, carrier specific surface area, and the carrier fill %
- Be able to calculate the liquid volume in an MBBR tank for known tank volume, carrier volume and carrier % void space
- Be able to calculate the BOD, $NH_3$-N, or $NO_3$-N removal rate for known values of the surface area removal rate (SARR) and design carrier surface area
- Be able to calculate an estimated effluent BOD, $NH_3$-N, or $NO_3$-N concentration based on known values of the appropriate loading rate, estimated removal rate, and design wastewater flow rate
- Be able to use the sample spreadsheet included with the course to make process design calculations for a single stage BOD removal process in either U.S. units or S.I. units.

- Be able to use the sample spreadsheet included with the course to make process design calculations for a single stage nitrification process in either U.S. units or S.I. units.

- Be able to make process design calculations for a post-Anoxic denitrification MBBR process, including required tank sizes, estimated effluent concentrations, alkalinity requirement and carbon source requirement.

- Be able to make process design calculations for a pre-anoxic denitrification MBBR process, including required tank sizes, estimated effluent concentrations, and alkalinity requirements.

## 3. Topics Covered in this Course

I. General Information about the MBBR Wastewater Treatment Process

   A. Initial Development of the Process
   B. General Description of the Process
   C. The MBBR Media Support Carrier System
   D. MBBR Process Alternatives

II. MBBR Process Design Calculations – BOD Removal and Nitrification

   A. Overview of MBBR Process Design Calculations
   B. Single Stage BOD Removal Process Design Calculations
   C. Single Stage Tertiary Nitrification Design Calculations
   D. Two-Stage BOD Removal Process Design Calculations
   E. Two-Stage BOD Removal/Nitrification Design Calculations

III. MBBR Denitrification Processes

   A. Introduction to MBBR Denitrification Processes
   B. Post-Anoxic Denitrification Process Design Calculations
   C. Pre-Anoxic Denitrification Process Design Calculations

IV. Summary

V. References

# 4. General Information about the MBBR Wastewater Treatment Process

## Initial Development of the Process

The MBBR process for wastewater treatment was invented and initially developed by Professor Hallvard Ǿdegaard in the late 1980s at the Norwegian University of Science and Technology. Use of this wastewater treatment process has spread rapidly. Per Ǿdegaard, 2014 (Reference #1 at the end of this course), there were already more than 800 MBBR wastewater treatment plants in more than 50 countries at that time (2014), with about half treating domestic wastewater and about half treating industrial wastewater. At least part of the reason for the interest in the MBBR process is its small footprint in comparison with other biological treatment processes. The tank volume needed for a MBBR process is typically significantly less than that needed for either an activated sludge process or a trickling filter designed to treat the same wastewater flow.

## General Description of the Process

The MBBR process is an attached growth biological wastewater treatment process. That is, the microorganisms that carry out the treatment are attached to a solid medium, as in trickling filter or RBC systems. By contrast, in a suspended growth biological wastewater treatment process, like the activated sludge process, the microorganisms that carry out the treatment are kept suspended in the mixed liquor in the aeration tank.

In the conventional attached growth, biological treatment processes, like trickling filter or RBC systems the microorganisms are attached to a medium that is fixed in place and the wastewater being treated flows past the surfaces of the medium with their attached biological growth. In contrast, an MBBR process utilizes small plastic carrier media that are described in more detail in the next section. The MBBR treatment processes typically take place in a tank similar to an activated sludge aeration tank. The carrier media are kept suspended by a diffused air aeration system for an aerobic process or by a mechanical mixing system for an anoxic or anaerobic process, as indicated in figures 1 and 2 below. A sieve is typically used at the tank exit to keep the carrier media in the tank.

Primary clarification is typically used ahead of the MBBR tank. Secondary clarification is also typically used, but there is no recycle activated sludge sent back into the process.

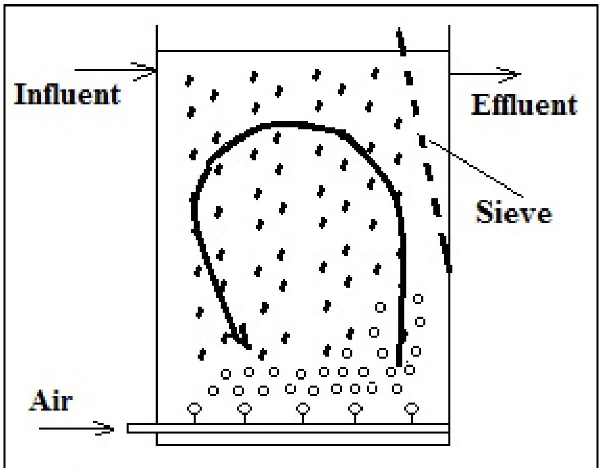


Figure 1, Aerobic MBBR Reactor

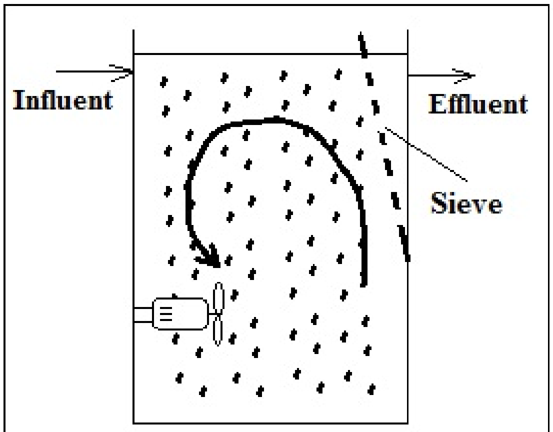


Figure 2, Anoxic or Anerobic MBBR Reactor

## The MBBR Media Support Carrier System

MBBR processes use plastic media support carriers similar to those shown in Figure 3. As shown in the figure, the carrier is typically designed to have a high surface area per unit volume, so that there is a lot of surface area on which the microorganisms attach and grow. Media support carriers like those shown in Figure 3 are available from numerous vendors. Two properties of the carrier are needed for the process design calculations to be described and discussed in this course. Those properties are the specific surface area in $m^2/m^3$ and the void ratio. The specific surface area of MBBR carriers is typically in the range from 350 to 1200 $m^2/m^3$ and the void ratio typically ranges from 60% to 90%. Design values for these carrier properties should be obtained from the carrier manufacturer or vendor.


Figure 3, Typical MBBR Media Support Carriers

## MBBR Process Alternatives

The MBBR wastewater treatment process is quite flexible and can be used in several different ways. There will be a description and discussion of the following six MBBR process alternatives in this course:

1. Single stage BOD removal
2. Single stage tertiary Nitrification
3. Two-stage BOD removal
4. Two-stage BOD removal and Nitrification
5. Pre-Anoxic BOD removal/Nitrification/Denitrification
6. Post-Anoxic BOD removal/Nitrification/Denitrification

Flow diagrams for these six MBBR process alternatives are shown in the diagram below:

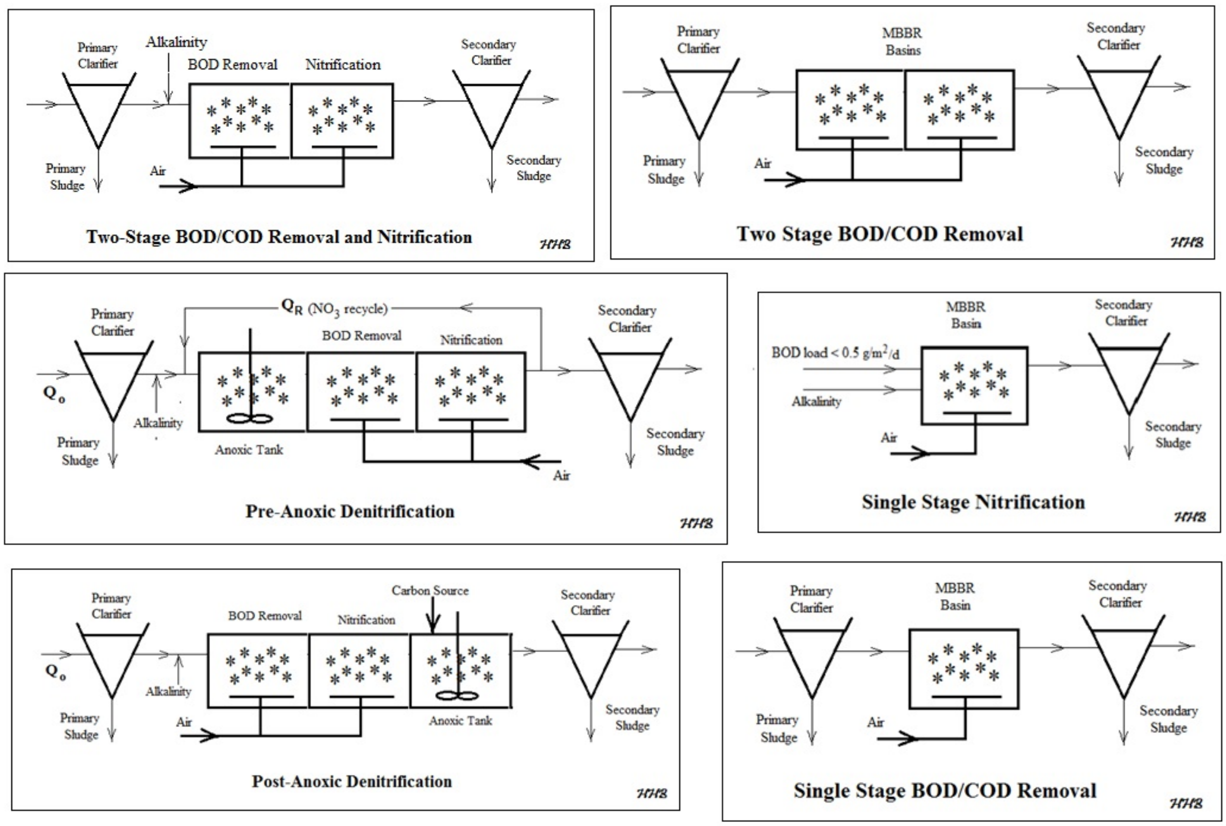



**Figure 4.** MBBR Wastewater Treatment Process Alternatives

Each of the process alternatives shown in Figure 4 will be covered in more detail later in the course.

# 5. MBBR Process Design Calculations for BOD Removal and Nitrification

## Overview of MBBR Process Design Calculations

The key empirical design parameter used to determine the required MBBR tank size is the surface area loading rate (SALR) in g/m$^2$/d. The g/d in the SALR units refers to the g/d of the parameter being removed and the m$^2$ in the SALR units refers to the surface area of the carrier. Thus, for BOD removal the SALR would be g BOD/day entering the MBBR tank per $m^2$ of carrier surface area. For a nitrification reactor, the SALR would be g $NH_3$-N/day entering the MBBR tank per $m^2$ of carrier surface area. Finally, for denitrification design, the SALR would be g $NO_3$-N/day per $m^2$ of carrier surface area.

For any of these processes, a design value for SALR can be used together with design values of wastewater flow rate and BOD, ammonia or nitrate concentration, to calculate the required carrier surface area in the MBBR tank. The design carrier volume can then be calculated using a known value for the carrier specific surface area ($m^2/m^3$). Finally, a design value for the carrier fill % can be used to calculate the required tank volume.

Process design calculations for each of the process alternatives shown in **Figure 4** will be covered in the next several sections.

## Single Stage BOD Removal Process Design Calculations

An MBBR single stage BOD removal process may be used as a free-standing secondary treatment process or as a roughing treatment prior to another secondary treatment process, in some cases to relieve overloading of an existing secondary treatment process. In either case the key design parameter for sizing the MBBR tank is the surface area loading rate (SALR), typically with units of $g/m^2$/day, that is g/day of BOD coming into the MBBR tank per $m^2$ of carrier surface area. Using design values for wastewater flow rate and BOD concentration entering the MBBR tank, the loading rate in g BOD/day can be calculated. Then dividing BOD loading rate in g/day by the SALR in $g/m^2$/day gives the required carrier surface area in $m^2$. The carrier fill %, carrier specific surface area, and carrier % void space can then be used to calculate the required carrier volume, tank volume and the volume of liquid in the reactor. A typical flow diagram for a single stage MBBR BOD removal process is shown in **Figure 5** below.

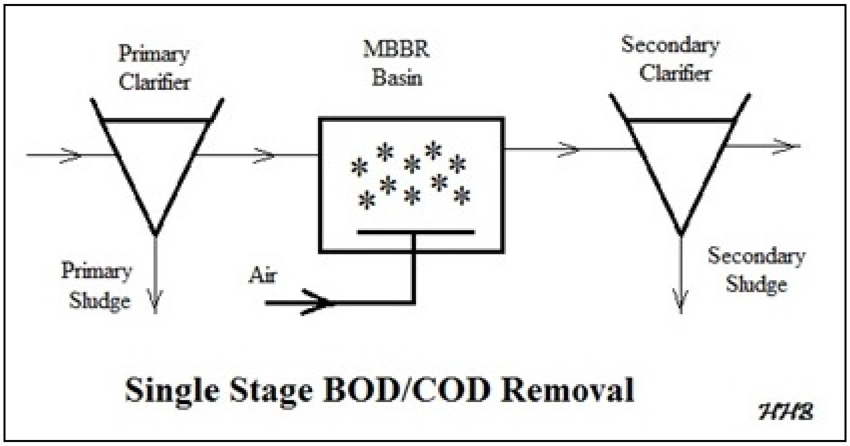



**Figure 5.** Single Stage MBBR Process for BOD/COD Removal

The equations for making those calculations are as follows:

**1. BOD loading rate = Q*$S_o$*8.34*453.59**

where: **Q** is the wastewater flow rate into the MBBR reactor in MGD
**$S_o$** is the BOD concentration in that influent flow in mg/L
**8.34** is the conversion factor from mg/L to lb/MG
**453.59** is the conversion factor from lb to g
The calculated **BOD loading rate** will be in g/day.

**2. required carrier surface area = BOD Loading Rate/SALR**

where: **BOD Loading Rate** is in g/day
**SALR** is the design surface area loading rate in g/m$^2$/day
The calculated **required carrier surface area** will be in m$^2$.

**3. required carrier volume**
**= required carrier surface area/carrier specific surface area**

where: **required carrier surface Area** is in m$^2$
**carrier specific surface Area** is in m$^2$/m$^3$
The calculated **required carrier volume** will be in m$^3$.

**4. required tank volume = required carrier volume/carrier fill %**

where: **required tank volume** will be in the same units as **required carrier volume.**

**5. liquid volume in tank = required tank volume**
**– [required carrier volume(1 – carrier % void space)]**

where: all three volumes will be in the same units.

Note that volumes calculated in $m^3$ can be converted to $ft^3$ by multiplying by $3.2808^3$ (or 35.313) $ft^3/m^3$.

Although hydraulic retention time (HRT) is not typically used as a primary design parameter for MBBR reactors, it can be calculated at the design wastewater flow rate, if the liquid volume in the tank is known. Also, if a design peak hour factor is specified, then the HRT at peak hourly flow can be calculated as well. The equations for these calculations are as follows:

**1. Ave. $HRT_{des\ ave}$ = liquid vol. in tank*7.48)/[Q*$10^6$/(24*60)]**

where: **liquid vol. in tank** is in $ft^3$
**Q** is in MGD
**7.48** is the conversion factor for $ft^3$ to gal
**$10^6$** is the conversion factor for MG to gal
**24*60** is the conversion factor for days to min
**Ave. $HRT_{des\ ave}$** will be in min

**2. Ave. $HRT_{peak\ hr}$ = Ave. $HRT_{des\ ave}$/Peak Hour Factor**

where: **Ave. $HRT_{peak\ hr}$** will also be in min

**Table 1** on the next page shows typical SALR design values for BOD removal in MBBR reactors. Reference #2 at the end of the course is the source for the values in **Table 1**.

**Table 1.** Typical Design SALR Values for BOD Removal

| Typical Design Values for MBBR reactors at 15°C | | |
|---|---|---|
| Purpose | Treatment Target % Removal | Design SALR $g/m^2$-d |
| BOD Removal | | |
| High Rate | 75 - 80 ($BOD_7$) | 25 ($BOD_7$) |
| Normal Rate | 85 - 90 ($BOD_7$) | 15 ($BOD_7$) |
| Low Rate | 90 - 95 ($BOD_7$) | 7.5 ($BOD_7$) |

**Example #1:** A design wastewater flow of 0.2 MGD containing 180 mg/L BOD (in the primary effluent) is to be treated in an MBBR reactor.

a) What is the BOD loading rate to the reactor in g/day?
b) What is a suitable design SALR to use for a target % removal of 90-95% ?
c) If the MBBR carrier has a specific surface area of 500 $m^2/m^3$ and design carrier fill % of 40%, what would be the required volume of carrier and required MBBR tank volume?
d) If the design carrier % void space is 60%, what would be the volume of liquid in the MBBR reactor.
e) If the design peak hour factor is 4, calculate the average hydraulic retention time at design average wastewater flow and at design peak hourly wastewater flow.

**Solution:**

a) The BOD loading rate will be (0.2 MGD)(180 mg/L)(8.34 lb/MG/mg/L) = 300.2 lb/day = (300.2 lb/day)*(453.59 g/lb) = **136,186 g BOD/day**
b) From Table 1 above, a suitable design SALR value for BOD removal with a target BOD removal of 90–95% would be **7.5 $g/m^2$/day**
c) Required carrier surface area = (136,186 g/day)/(7.5 $g/m^2$/day) = 18,158 $m^2$. Required carrier volume = 18,158 $m^2$/500 $m^2/m^3$. = 36.316 $m^3$ = (36.316 $m^3$)(35.313 $ft^3/m^3$) = **1282 $ft^3$**.

For 40% carrier fill: Required tank volume = 1282 $ft^3$/0.40 = **3206.2 $ft^3$**.

d) The volume of liquid in the reactor can be calculated as:

tank volume – [carrier volume( 1 – void %)], Thus the volume of liquid is: 3206.2 – [1282(1 – 0.60)] = **2693.2 ft$^3$**.

e) The HRT at design ave ww flow can be calculated as:
$HRT_{des\ ave}$ = reactor liquid volume*7.48/[Q*10$^6$/(24*60)] = 2693.2*7.48/[0.2*10$^6$/(24*60)] = **145 min**

$HRT_{peak\ hr}$ = $HRT_{des\ ave}$/peak hour factor = 145/4 = **36 min**

**Use of an Excel Spreadsheet**

The type of calculations just discussed can be done conveniently using an Excel spreadsheet. The screenshot in **Figure 6** below shows a screenshot of worksheet 2 of the course spreadsheet set up to make the calculations just described for **Example #1**. The worksheet shows user input values of the given information entered in the blue cells. The values in the yellow cells are calculated by the spreadsheet using the equations presented and discussed above. The values calculated by the spreadsheet for the following parameters are the same as those shown in the solution to **Example #1** above: i) the BOD loading in g/day, ii) the required tank volume, iii) the liquid volume in the tank, iv) the hydraulic retention time at design average flow, and v) the hydraulic retention time at peak hourly flow.

You may have noticed that there are a few additional calculations in the worksheet screenshot. If the user selected tank shape is "rectangular," the worksheet calculates the tank length and width for the calculated required tank volume. If the user selected tank shape is cylindrical, the worksheet will calculate the tank diameter. These calculations simply use the formulas for the volume of a rectangular tank (V = L*W*H) or for the volume of a cylindrical tank ($V = \pi D^2 H/4$), with user entered values for L:W ratio being used for rectangular tank calculations and the user entered value for the liquid depth in the tank, H, being used by both. The worksheet also calculates an estimated effluent BOD concentration, which is discussed in the next section (after Example #2, which illustrates a solution with S.I. units).

**MBBR Process Design Calculations - U.S. units**

Single-Stage Process for BOD Removal

**Instructions***: Enter values in blue boxes. Spreadsheet calculates values in yellow boxes*

**1. General Inputs**

| | | | | | |
|---|---|---|---|---|---|
| | | | Data points for SARR/SALR vs SALR | | |
| Design ww Flow Rate, **Q** = | 0.2 | MGD | **SALR** (g/m²/d): | 7.5 | 15.0 |
| Prim. Effl. BOD, $\mathbf{S_o}$ = | 180 | mg/L | **SARR/SALR:** | 0.925 | 0.875 |
| Peak Hour Factor = | 4 | | (default values above are based on the table of typica values of % BOD removal vs SALR at the right) | | |
| Design Value of BOD Surface | | | Slope, SARR/SALR vs SALR: | | -0.007 |
| Area Loading Rate (SALR) = | 7.5 | g/m²/d | Intercept, SARR/SALR vs SALR: | | 0.975 |
| See information on typical design | | | Est. of SARR/SALR Rato = | | 0.925 |
| values for SALR below right. | | | (Surf. Area Removal Rate/Surf. Area Loading Rate) (for SALR value specified at left) | | |

**2. Calculation of Carrier Volume and Required Tank Volume & Dimensions**

| | | | | | |
|---|---|---|---|---|---|
| **Inputs** | | | Liquid Depth in Tank = | 8 | ft |
| Carrier Spec. Surf. Area = | 500 | m²/m³ | Tank L:W ratio = | 1.5 | |
| (value from carrier mfr/vendor) | | | (target L:W - only used if tank is rectangular) | | |
| Design Carrier Fill % = | 40% | | Click on green box and then on | | |
| (Carrier fill % is typically between 30% and 70%. Lower values are more conservative, allowing future capacity expansion or reduction of SALR by adding more carrier.) | | | arrow to Select Tank Shape: | rectangular | |
| | | | Carrier % Void Space = | 60% | |
| | | | (from carrier mfr/vendor - only needed to calculate hydraulic detention time) | | |

| | | | | | |
|---|---|---|---|---|---|
| **Calculations** | | | | | |
| BOD Daily Loading = | 300.2 | lb/day | Calculated Tank Volume = | 90.8 | m³ |
| | 136186 | g/day | = | 3206.2 | ft³ |
| | | | = | 23983 | gal |
| Carrier Surf. Area needed = | 18158.1 | m² | | | |
| Calculated Carrier Volume = | 36.316 | m³ | Calculated Tank Width = | 16.3 | ft |
| | | | Calculated Tank Length = | 24.5 | ft |
| Tank Liquid Volume = | 2693.2 | ft³ | Nominal Hydraulic Retention Time at | | |
| | | | Design Average Flow = | 145 | min |
| Estimate of BOD Surface Area | | | Peak Hourly Flow = | 36 | min |
| Removal Rate, **SARR** = | 6.94 | g/m²/d | | | |
| Est. of BOD Removal Rate: | 125972 | g/day | Estimated Effl BOD Conc.: | 14 | mg/L |
| | 277.7 | lb/day | If the estimated Effl. BOD conc. is too high, the design value of SALR (in cell C13) should be reduced. | | |

**Figure 6.** Screenshot – Single Stage BOD Removal Calculations – U.S. units

**Example #2:** (working with S.I. units) Repeat Example #1 if the wastewater flow is specified as 757 $m^3$/d instead of 0.2 MGD. The rest of the given information remains the same. The wastewater flow containing 180 mg/L BOD is to be treated in an MBBR reactor.

a) What is the BOD loading rate to the reactor in g/day?
b) What would be a suitable design SALR to use for a target removal of 90-95% ?
c) If the MBBR carrier has a specific surface area of 500 $m^2/m^3$ and design carrier fill % of 40%, what would be the required volume of carrier and required MBBR tank volume?
d) If the design carrier % void space is 60%, what would be the volume of liquid in the MBBR reactor.
e) If the design peak hour factor is 4, calculate the average hydraulic retention time at design average wastewater flow and at design peak hourly wastewater flow.

**Solution:**

a) The BOD loading rate will be (757 $m^3$/d)(180 g/$m^3$) = **136,260 g BOD/day**

b) From Table 1 above, a suitable design SALR value for BOD removal with a target BOD removal of 90–95% would be **7.5 g/$m^2$/day**

c) Required carrier surface area = (136,260 g/day)/(7.5 g/$m^2$/day) = 18,168 $m^2$.

d) The volume of liquid in the reactor can be calculated as:
tank volume – [carrier volume( 1 – void %)], Thus the volume of liquid is: 90.8 – [36.34(1 – 0.60)] = **76.3 $m^3$**.

e) The HRT at design ave ww flow can be calculated as:
$HRT_{des\ ave}$ = reactor liquid volume/[Q/(24*60)]
= 76.3/[757/(24*60)] = **145 min**

$HRT_{peak\ hr}$ = $HRT_{des\ ave}$/peak hour factor = 145/4 = **36 min**

The Excel spreadsheet screenshot on the next page (from worksheet 3 in the course spreadsheet) shows the spreadsheet solution to Example #2. There are slight differences from the solution with U.S. units due to rounding of the design flow conversion from MGD to $m^3$/s.

## MBBR Process Design Calculations - S.I. units

### Single-Stage Process for BOD Removal

**Instructions**: ***Enter values in blue boxes. Spreadsheet calculates values in yellow boxes***

| | | | | | |
|---|---|---|---|---|---|
| **1. General Inputs** | | | | | |
| | | | Data points for SARR/SALR vs SALR | | |
| Design ww Flow Rate, **Q** = | 757 | $m^3/d$ | **SALR** ($g/m^2/d$): | 7.5 | 15.0 |
| Prim. Effl. BOD, $S_o$ = | 180 | mg/L | **SARR/SALR:** | 0.925 | 0.875 |
| Peak Hour Factor = | 4 | | **(default values above are based on the table of typica** | | |
| | | | **values of % BOD removal vs SALR at the right)** | | |
| Design Value of BOD Surface | | | Slope, SARR/SALR vs SALR: | | -0.007 |
| Area Loading Rate (SALR) = | 7.5 | $g/m^2/d$ | Intercept, SARR/SALR vs SALR: | | 0.975 |
| **See information on typical design** | | | Est. of SARR/SALR Rato = | | 0.925 |
| **values for SALR below right.** | | | (Surf. Area Removal Rate/Surf. Area Loading Rate) | | |
| | | | (for SALR value specified at left) | | |
| **2. Calculation of Carrier Volume and Required Tank Volume & Dimensions** | | | | | |
| **Inputs** | | | Liquid Depth in Tank = | 2 | m |
| Carrier Spec. Surf. Area = | 500 | $m^2/m^3$ | Tank L:W ratio = | 1.5 | |
| (value from carrier mfr/vendor) | | | **(target L:W - only used if tank is rectangular)** | | |
| Design Carrier Fill % = | 40% | | **Click on green box and then on** | | |
| **(Carrier fill % is typically between 30% and** | | | **arrow to Select Tank Shape:** | **rectangular** | |
| **70%. Lower values are more conservative,** | | | Carrier % Void Space = | 60% | |
| **allowing future capacity expansion or** | | | **(from carrier mfr/vendor - only needed to** | | |
| **reduction of SALR by adding more carrier.)** | | | **calculate hydraulic detention time)** | | |
| **Calculations** | | | | | |
| BOD Daily Loading = | 136.3 | kg/day | Calculated Tank Volume = | 90.8 | $m^3$ |
| | 136260 | g/day | | | |
| Carrier Surf. Area needed = | 18168 | $m^2$ | | | |
| Calculated Carrier Volume = | 36.34 | $m^3$ | Calculated Tank Width = | 5.0 | m |
| | | | Calculated Tank Length = | 7.5 | m |
| Tank Liquid Volume = | 76.3 | $m^3$ | Nominal Hydraulic Retention Time at | | |
| | | | Design Average Flow = | 145 | min |
| Estimate of BOD Surface Area | | | Peak Hourly Flow = | 36 | min |
| Removal Rate, **SARR** = | 6.94 | $g/m^2/d$ | | | |
| Est. of BOD Removal Rate: | 126041 | g/day | Calculated Effl BOD Conc.: | 14 | mg/L |
| | | | **If the calculated Effl. BOD conc. is too** | | |
| | | | **high, the design value of SALR** | | |
| | | | **(in cell C13) should be reduced.** | | |

**Figure 7.** Screenshot – Single Stage BOD Removal Calculations – S.I. units

## Estimation of Effluent Concentration

Use of an estimated surface area removal rate (SARR) allows calculation of the estimated effluent concentration of the parameter being removed. That is, for BOD removal, the estimated effluent BOD concentration can be calculated. For nitrification, the estimated effluent ammonia nitrogen concentration can be calculated and for denitrification, the estimated effluent nitrate nitrogen concentration can be calculated.

Based on graphs and tables provided in several of the references at the end of this course, the SARR/SALR ratio for all the different types of MBBR treatment being covered in this course ranges from about 0.8 to nearly 1.0 over the range of SALR values typically used. The SARR/SALR ratio is nearly one at very low SALR values and decreases as the SALR value increases.

The upper right portion of the screenshot on the previous two pages illustrates an approach for estimating a value for the SARR/SALR ratio for a specified design value of SALR. In the four blue cells at the upper right, two sets of values for SARR/SALR and SALR are entered. In this case, they are based on the typical values of % BOD removal vs SALR in Table 1 above. In the yellow cells below those entries, the slope and intercept of a SARR/SALR vs SALR straight line are calculated using the Excel SLOPE and INTERCEPT functions. Then the SARR/SALR ratio is calculated for the specified design value of SALR.

Note that the ratio SARR/SALR is equal to the % BOD removal expressed as a fraction. This can be shown as follows:

BOD removal rate in g/day = (SARR in g/m$^2$/d)(Carrier Surf. Area in m$^2$)

BOD rate into plant in g/day = (SALR in g/m$^2$/d)(Carrier Surf. Area in m$^2$)

**% BOD removal** = (BOD removal rate/BOD rate into plant)*100%

= (100%)(SARR* Carrier Surf Area)/(SALR*Carrier Surf Area)

**= (SARR/SALR)100%**

Note that the value of **0.925** for the **SARR/SALR** ratio at **SALR = 7.5 g/m$^2$/d** was obtained from **Table 1** above as the midpoint of the 90-95% estimated % BOD removal for **SALR = 7.5 g/m$^2$/d**. Similarly, the value of **0.875** for the **SARR/SALR** ratio at **SALR = 15 g/m$^2$/d** was obtained from **Table 1** above as the midpoint of the 85-90% estimated % BOD removal for **SALR = 15 g/m$^2$/d**.

At the bottom of the screenshot worksheet, the estimated value of the surface area removal rate (SARR) is calculated. It is used to calculate an estimated BOD removal rate in g BOD/day and lb BOD/day. Then an estimate of the effluent BOD concentration is calculated. The equations for these calculations are as follows:

1. estimated SARR = (calculated SARR/SALR)(design value of SALR)

2. estimated BOD removal rate = (estimated SARR)(carrier surface area)

3. estimated effluent BOD conc.
   = [(BOD loading rate - estimated BOD removal rate)/$Q_o$]/8.34

The calculations are exactly the same for S.I. units except that the 8.34 conversion factor isn't needed in the last calculation.

**Example #3:** Calculate the estimated effluent BOD concentration for the wastewater flow described in **Example #1** being treated in the MBBR reactor sized in **Example #1**.

**Solution:** The solution is included in the **Figure 6** and **Figure 7** spreadsheet screenshots that were used for the solutions to **Example #1** and **Example #2** above. The pair of points for **SARR/SALR vs SALR** that were discussed above and are shown on the **Figure 6** and **Figure 7** screenshots lead to the following values for the slope and intercept for the **SARR/SALR vs SALR** line: **Slope = -0.007, Intercept = 0.975**.

Thus, the estimated **SARR/SALR** ratio for the given **SALR** value of **7.5 g/m$^2$/d** would be calculated as: **SARR/SALR = - (0.007)(7.5) + 0.975 = 0.925**

The SARR value can be calculated as:

**SARR = (SARR/SALR)(SALR) = (0.925)(7.5) = 6.94 g/m$^2$/d**

Then, the estimated BOD removal rate can be calculated as:

**est BOD removal rate = (est SARR)(carrier surface area)**

**= (6.94 g/m$^2$/d)(18,158.1 m$^2$) = 125,972 g/d = 125,772/453.59 lb/day**

**est BOD removal rate = 277.7 lb/day (or 126,041 g/day)**

The estimated effluent BOD concentration can then be calculated from the equation:

est effluent BOD conc. = [(BOD loading rate - est BOD removal rate)/$Q_o$]/8.34

Substituting calculated and given values:

**Est. effluent BOD conc.** = [(300.2 – 277.7)/0.2]/8.34 = **14 mg/L**

Note that this **14 mg/L** value for the **estimated effluent BOD** concentration is shown near the bottom of the **Figure 6** and **Figure 7** spreadsheet screenshots.

## 6. Single Stage Nitrification Process Design Calculations

A single stage MBBR nitrification process would typically be used as a tertiary treatment process following some type of secondary treatment that reduced the BOD to a suitable level. A typical flow diagram for a single stage MBBR process for nitrification is shown in **Figure 8** below. Note that alkalinity is used in the nitrification process, so alkalinity addition is typically required. As shown on the diagram, the influent BOD level should be low enough so that the BOD load to the nitrification process is less than 0.5 $g/m^2$/day. Higher BOD loading to an MBBR nitrification reactor results in too many BOD removing microorganisms and not enough nitrification microorganisms.

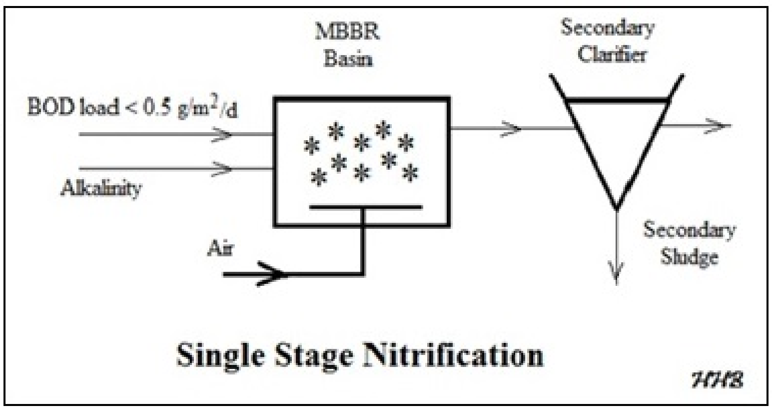



**Figure 8**. Single Stage MBBR Process for Nitrification

The process design calculations for this single stage MBBR process are similar to those described above for a single stage BOD removal MBBR process, but the design SALR value for nitrification can be calculated rather than using an empirical value from a table of typical values, as was done for BOD removal. The design SALR can be calculated using a kinetic model for the surface area removal rate (SARR) as a function of the dissolved oxygen concentration in the MBBR reactor and the bulk liquid ammonia nitrogen concentration, which is equal to the effluent ammonia nitrogen concentration assuming completely mixed conditions in the MBBR tank.

The kinetic model to be discussed here is from Metcalf and Eddy (2014), Figure 9-25 [ attributed to Odegaard (2006) ] and Equation 9-48. This figure and equation will now be shown and discussed briefly. **Figure 9** below was prepared based on Metcalf and Eddy's Figure 9-25 and their Equation 9-48 (shown below). Note that the figure and equation are for operation at 15°C. Correction of the SARR and SALR for some other operational temperature can be done with the equation: $SARR_T = SARR_{15}\theta^{(T-15)}$ where T is the design operational temperature in °C. From Salvetti, et.al (2006): **$\theta$ = 1.058** for D.O. limited conditions and **$\theta$ = 1.098** if ammonia nitrogen concentration is the limiting factor.

Equation 9-48 from Metcalf and Eddy (2014) is:

**$SARR = [ N_e/(2.2 + N_e)]*3.3$** , **$N_e$ =** effluent ammonia N conc.

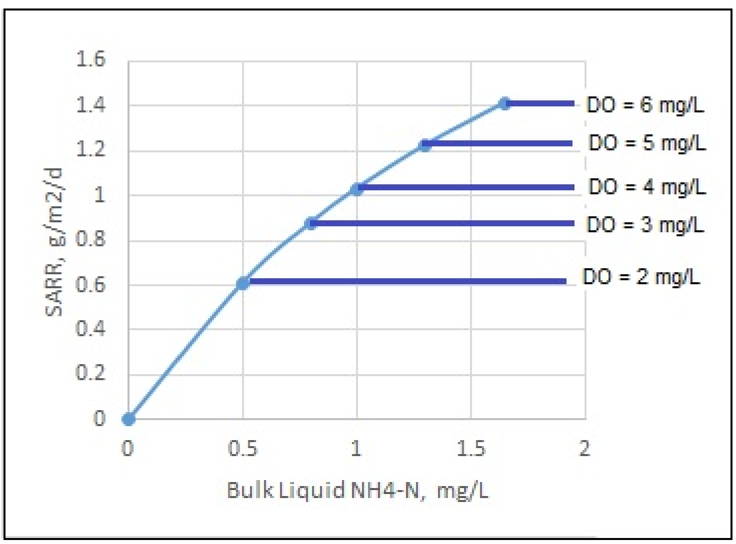



**Figure 9**. Adapted from Metcalf & Eddy (2014), Fig 9-25

The horizontal lines in **Figure 9** show the nitrification **SARR** under DO limiting conditions for each of the DO levels shown. The **SARR** will be DO limited when the **$NH_3$-N** concentration is above the value at the left end of the horizontal line for each D.O. level. When the **$NH_3$-N** concentration is below that value, then the **SARR** is ammonia concentration limited and the **SARR** is a function of the effluent **$NH_3$-N** concentration per the equation: **SARR = [ $N_e$/(2.2 + $N_e$)]*3.3.**

As shown previously for BOD removal, **SALR/SARR = % BOD removal**. Similarly, for nitrification, **SALR/SARR = % $NH_3$-N removal**. After the **SARR** has been determined, the **SALR** can be calculated as: **SALR = SARR/% removal**.

The maximum **SARR** for each of the D.O. levels shown in **Figure 11** are shown in **Table 2** below, along with the ammonia nitrogen concentration above which the **SARR** will be at that maximum value.

**Table 2.** Values of **$SARR_{max}$** and **$NH_3$-$N_e$** @ **$SARR_{max}$**

| D.O. | $SARR_{max}$ | min $NH_3$-$N_e$ @ $SARR_{max}$ |
|---|---|---|
| mg/L | $g/m^2/d$ | mg/L |
| 2 | 0.61 | 0.5 |
| 3 | 0.88 | 0.8 |
| 4 | 1.03 | 1 |
| 5 | 1.23 | 1.3 |
| 6 | 1.41 | 1.65 |

The process design calculations for single stage nitrification are illustrated in the next example.

**Example #4:** A design secondary effluent flow of 0.2 MGD has the following characteristics: 15 mg/L BOD, 35 mg/L TKN, and alkalinity of 140 mg/L as $CaCO_3$. This flow is to be treated in a single stage nitrification MBBR reactor. The target effluent $NH_3$-N is 3.3 mg/L. The dissolved oxygen is to be maintained at 3.0 mg/L in the MBBR reactor. The design minimum wastewater temperature is to be 45°F.

a) Determine an appropriate $NH_3$-N surface area loading rate (SALR) for this nitrification process, in g $NH_3$-N/$m^2$/d.
b) What is the $NH_3$-N loading rate to the reactor in g/day?
c) If the MBBR carrier has a specific surface area of 500 $m^2/m^3$ and design carrier fill % of 40%, what would be the required volume of carrier and required MBBR tank volume?
d) Calculate the BOD surface area loading rate (SALR) to ensure that it is less than 0.5 g BOD/$m^2$/day.
e) If the design carrier % void space is 60%, what would be the volume of liquid in the MBBR reactor.
f) If the design peak hour factor is 4, calculate the average hydraulic retention time at design average wastewater flow and at design peak hourly wastewater flow.
g) Calculate the alkalinity requirement in lb/day as $CaCO_3$ and in lb/day $NaHCO_3$.

**Solution:**

The solution, as calculated with the course spreadsheet, is shown in the screenshots in **Figure 10** and **Figure 11** below. A summary of the calculations is given here:

**a)** The D.O. limited **SARR** can be obtained as **$SARR_{max}$** from **Table 2** for the specified D.O level, and the minimum ammonia nitrogen concentration for that **SARR** value can be obtained from the same table. The values from **Table 2**, for a D.O. of 3.0 are: **$SARR_{max}$ = 0.88 g/$m^2$/d** and minimum **$NH_3$-$N_e$** for **$SARR_{max}$ = 0.80 mg/L.** (in the worksheet shown in the **Figure 12** screenshot, these two values are obtained using Excel's VLOOKUP function from a table like **Table 2**, above that is on the worksheet.

The **SARR** for the design D.O. and ammonia nitrogen removal at 15$^o$C will then be equal to **$SARR_{max}$** if the target effluent ammonia nitrogen concentration is greater than the 0.80 mg/L value determined above. If the target effluent ammonia nitrogen concentration is less than 0.80 mg/L, then the SARR needs to be calculated using Metcalf & Eddy's equation 9-48. In this case, the target effluent $NH_3$-N of 3.3 mg/L is greater than 0.8 mg/L, so the SARR at 15$^o$C is 0.88 g/$m^2$/d.

The design value for the SARR at the design minimum wastewater temperature can then be calculated as: $SARR_T = SARR_{15}\theta^{(T-15)}$, where the WW temperature must be in $^o$C. Since this case has D.O. limited conditions, **$\theta$ = 1.058**. Carrying out this calculations gives: **design value of SALR = 0.63 g/$m^2$/d**.

b) The Nitrate loading rate will be (0.2 MGD)(35 mg/L)(8.34 lb/MG/mg/L) = 58.4 lb/day = (58.4 lb/day)*(453.59 g/lb) = **26,481 g BOD/day**

c) Required carrier surface area = (26,481 g/day)/(0.63 g/$m^2$/day) = 42,255 $m^2$.

Required carrier volume = 42,255 $m^2$/500 $m^2/m^3$. = 84.51 $m^3$ = (84.51 $m^3$)(35.313 $ft^3/m^3$) = **2984 $ft^3$**. **(84.51 $m^3$)**

For 40% carrier fill: Required tank volume = 2984 $ft^3$/0.40 = **7461 $ft^3$**. **(211.3 $m^3$)**

d) The BOD SALR will be (0.2 MGD)(15 mg/L)(8.34 lb/MG/mg/L)/(42255 $m^2$) = **0.27 g/$m^2$/day** (Note that this is less than 0.5 g/$m^2$/day as required.)

e) The volume of liquid in the reactor can be calculated as: tank volume – [carrier volume( 1 – void %)], Thus the volume of liquid is: 7461 – [2984(1 – 0.60)] = **6267 $ft^3$**. **(177.5 $m^3$)**

f) The HRT at design ave ww flow can be calculated as:
$HRT_{des\ ave}$ = reactor liquid volume*7.48/[Q*$10^6$/(24*60)] = 6267*7.48/[0.2*$10^6$/(24*60)] = **338 min**

$HRT_{peak\ hr}$ = $HRT_{des\ ave}$/peak hour factor = 338/4 = **84 min**

g) Calculation of the alkalinity requirement is shown in the **Figure 11** spreadsheet screenshot below. Using the equivalent weight of $CaCO_3$ as 50, the equivalent weight of $NaHCO_3$ as 84, the alkalinity use for nitrification as 7.14 g $CaCO_3$/g $NH_3$-N and the target effluent alkalinity as 80 mg/L as $CaCO_3$, give the calculated alkalinity requirement as 189.9 mg/L as $CaCO_3$. The rate of alkalinity addition needed can then be calculated as: (0.2 MGD)(189.9 mg/L)*8.34 = **316.8 lb/day as $CaCO_3$**. **(143.7 kg/day as $CaCO_3$)**. Multiplying this by the ratio of the equivalent weight of $NaHCO_3$ to the equivalent weight of $CaCO_3$ gives the daily $NaHCO_3$ requirement as **532.1 lb/day $NaHCO_3$**. **(241.4 kg/d as $NaHCO_3$).**

The S.I. version of the spreadsheet can be used with the 0.2 MGD wastewater flow rate specified as 757 $m^3$/d. All of the other inputs remain as given above. The answers in S.I. units (if different than the U.S. solution) are shown in parentheses at the end of each part of the solution above.

## MBBR Process Design Calculations - U.S. units
### Single Stage Tertiary Nitrification Process

**Instructions***: Enter values in blue boxes. Spreadsheet calculates values in yellow boxes*

**1. General Inputs**

| | | | | | |
|---|---|---|---|---|---|
| | | | Peak Hour Factor = | 4 | |
| | | | Target Effl $NH_4$-N Conc, $\mathbf{NH_4\text{-}N_e}$ = | 3.3 | mg/L |
| Design ww Flow Rate, **Q** = | 0.2 | MGD | Min Design Temp., **T** = | 45 | °F |
| Influent $NH_4$-N Conc. = | 35 | mg/L | | | |
| Influent BOD, $\mathbf{S_o}$ = | 15 | mg/L | **Click on cell H10 and on arrow to select D.O Conc.** | | |
| Prim. Effl. Alkalinity = | 140 | mg/L as $CaCO_3$ | D.O Conc. in Reactor = | 3.0 | mg/L |

**2. Preliminary Calculations - Design SALR value**

| | | | | | |
|---|---|---|---|---|---|
| % $NH_4$-N removal = | 91% | | $NH_4$-$N_e$ @ $SARR_{max}$ = | 0.80 | mg/L |
| Maximum SARR = | 0.88 | g/m²/d | SARR @ $NH_4$-Ne, 15°C, $\mathbf{SARR_{15}}$ = | 0.88 | g/m²/d |
| | | | SARR @ $NH_4$-Ne, T °C, $\mathbf{SARR_T}$ = | 0.57 | g/m²/d |
| SARR Temp. Coeff, **θ** = | 1.058 | | | | |
| | | | Design Value for **SALR** = | 0.63 | g/m²/d |

**3. Calculation of Carrier Volume and Required Tank Volume & Dimensions**

**Inputs**

| | | | | | |
|---|---|---|---|---|---|
| Carrier Spec. Surf. Area = | 500 | m²/m³ | Liquid Depth in Tank = | 8 | ft |
| (value from carrier mfr/vendor) | | | Tank L:W ratio = | 1.5 | |
| | | | **(target L:W - only used if tank is rectangular)** | | |
| Design Carrier Fill % = | 40% | | **Click on green box and then on arrow to Select Tank Shape:** | **rectangular** | |
| | | | Carrier % Void Space = | 60% | |
| | | | **(from carrier mfr/vendor - only needed to calculate hydraulic detention time)** | | |

**(Carrier fill % is typically between 30% and 70%. Lower values are more conservative, allowing future capacity expansion or reduction of SALR by adding more carrier.)**

**Calculations**

| | | | | | |
|---|---|---|---|---|---|
| | | | Calculated Tank Volume = | 211.3 | m³ |
| $NH_3$-N Daily Loading = | 58.4 | lb/day | = | 7461.1 | ft³ |
| | 26481 | g/day | = | 55809 | gal |
| Carrier Surf. Area needed = | 42255 | m² | Calculated Tank Width = | 24.9 | ft |
| Calculated Carrier Volume = | 84.510 | m³ | Calculated Tank Length = | 37.4 | ft |
| Tank Liquid Volume = | 6267.4 | ft³ | Nominal Hydraulic Retention Time at | | |
| | | | Design Average Flow = | 338 | min |
| BOD Surf. Loading Rate (SALR): | 0.27 | g/m²/d | Peak Hourly Flow = | 84 | min |

(should be < 0.5 g/m²/d in order to achieve a good nitrification rate)

**Fig. 10**. Screenshot of MBBR Process Design Calculations – Single Stage Nitrification

| | | | | | |
|---|---|---|---|---|---|
| **5. Alkalinity Requirement** | | | | | |
| **Input:** Target Effluent Alkalinity = | 80 | mg/L | | | |
| **Constants needed for Calculations:** | | | | | |
| Equiv Wt. of $CaCO_3$ = | 50 | g/equiv. | Equiv Wt. of $NaHCO_3$ = | 84 | g/equiv. |
| Alkalinity used for Nitrification = | 7.14 | g $CaCO_3$/g $NH_3$-N | | | |
| **Calculations** | | | | | |
| Alkalinity to be added = | 189.9 | mg/L as $CaCO_3$ | | | |
| Daily Alkalinity Requirement = | 316.8 | lb/day as $CaCO_3$ | | | |
| **For sodium bicarbonate use to add alkalinity:** | | | | | |
| Daily $NaHCO_3$ Requirement = | 532.1 | lb/day $NaHCO_3$ | | | |

**Figure 11**. Screenshot of MBBR Process Design Calculations – Alkalinity Requirements

# 7. Two-Stage BOD Removal Process Design Calculations

A two-stage MBBR BOD removal process may be used instead of a single stage process. In this case, a high SALR "roughing" treatment will typically be used for the first stage and a lower SALR will typically be used for the second stage. This will result in less total tank volume needed for a two-stage process than for a single stage process. Also, a two-stage MBBR process can typically achieve a lower effluent BOD concentration than a single stage MBBR process. A typical flow diagram for a two-stage MBBR process for BOD removal is shown in **Figure 12** below. Note that an intermediate clarifier is not typically used between stages.

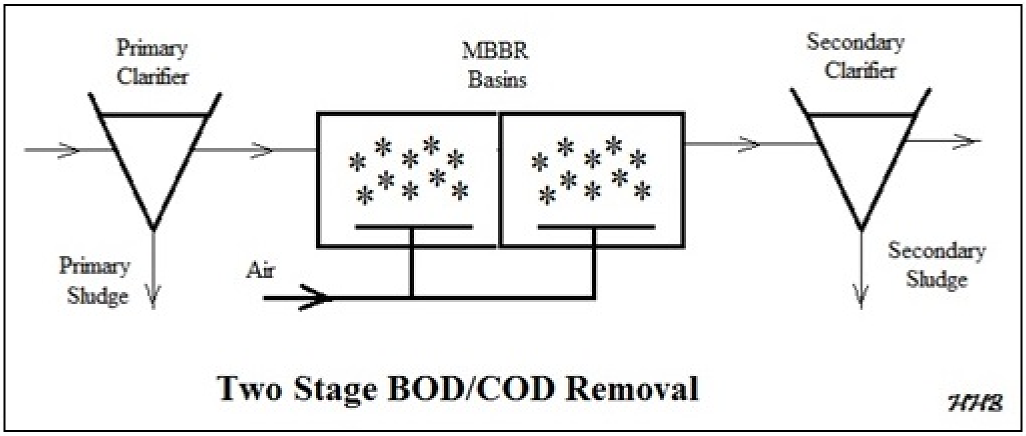



**Figure 12.** Two-Stage MBBR Process for BOD/COD Removal

The process design calculations for each stage of a two-stage MBBR process are essentially the same as shown for the single stage process above in section 5. These calculations are illustrated in **Example #5**.

**Example #5:** A design wastewater flow of 0.2 MGD (757 $m^3$/d) containing 180 mg/L BOD (in the primary effluent) is to be treated for BOD removal in a two stage MBBR reactor. The design SALR for the first stage is to be 25 g/$m^2$/d and the design SALR for the second stage is to be 7.5 g/$m^2$/d.

a) For the first stage calculate each of the following:
   i) The BOD loading
   ii) The required carrier volume for a carrier with specific surface area of 500 $m^2/m^3$
   iii) The required MBBR tank volume for a design carrier fill % of 40%
   iv) The volume of liquid in the MBBR reactor for design carrier % void space of 60%.
   v) The average hydraulic retention time at design average wastewater flow and at design peak hourly flow if the design peak hour factor is 4.
   vi) The estimated effluent BOD concentration from the first stage.

b) Calculate the same parameters for the second stage.

**Solution:** The solution as calculated with an Excel spreadsheet is shown in the spreadsheet screenshot in **Figure 13** and **Figure 14**. **Figure 13**, which is the top part of the spreadsheet, shows primarily the user input values. It also includes the calculation of the slope and intercept for the SARR/SALR vs SALR equation and the calculation of the estimated SARR for each stage. These calculations and the resulting SARR/SALR values are the same as those discussed above for the single-stage BOD removal MBBR process. The resulting values for SARR/SALR are **0.775** for the first stage with SALR = 25, and **0.925** for the second stage with SALR = 7.5.

The S.I. version of the spreadsheet can be used with the 0.2 MGD wastewater flow rate specified as 757 $m^3$/d. All of the other inputs remain as given above. The answers in S.I. units (if different than the U.S. solution) are shown in parentheses at the end of each part of the solution below

**Figure 14** is the bottom part of the spreadsheet and shows the calculated values as follows.

a) For the first stage:

i) The BOD loading rate will be (0.2 MGD)(180 mg/L)(8.34 lb/MG/mg/L) = 300.2 lb/day = (300.2 lb/day)*(453.59 g/lb) = **136,186 g BOD/day**

ii) Required carrier surface area = (136,186 g/day)/(25 g/$m^2$/day) = 5447.4 $m^2$.

Required carrier volume = 5447.4 $m^2$/500 $m^2/m^3$. = 10.895 $m^3$ = (10.895 $m^3$)($3.2808^3$ $ft^3/m^3$) = **384.7 $ft^3$**. (**10.895 $m^3$**)

iii) For 40% carrier fill: Required tank volume = 384.7 $ft^3$/0.40 = **961.9 $ft^3$**.

iv) The volume of liquid in the reactor can be calculated as:
tank volume – [carrier volume( 1 – void %)], Thus the volume of liquid is: 961.9 – [384.7(1 – 0.60)] = **808 $ft^3$**. (**22.88 $m^3$**)

v) The HRT at design ave ww flow can be calculated as:
$HRT_{des\ ave}$ = reactor liquid volume*7.48/[Q*$10^6$/(24*60)] =
808*7.48/[0.2*$10^6$/(24*60)] = **44 min**

$HRT_{peak\ hr}$ = $HRT_{des\ ave}$/peak hour factor = 44/4 = **11 min**

Calculation of the estimated effluent BOD concentration from the first stage as shown above for the single stage process gives a value of **41 mg/L.**

# MBBR Process Design Calculations - U.S. units

## Two-Stage Process for BOD Removal

**Instructions:** ***Enter values in blue boxes. Spreadsheet calculates values in yellow boxes***

### I. Wastewater Parameter Inputs

**1. Parameters for Both First and Second Stage**

Design ww Flow Rate, **Q** = 0.2 MGD

Peak Hour Factor = 4

**2. Parameters for First Stage:**

Prim. Effl. BOD, $S_{o1}$ = 180 mg/L

Design Value of BOD Surface Area Loading Rate (SALR) = 25 g/m²/d

**See information on typical design values for SALR below right.**

Data points for SARR/SALR vs SALR

| | | |
|---|---|---|
| **SALR** (g/m²/d): | 7.5 | 25.0 |
| **SARR/SALR:** | 0.925 | 0.775 |

**(default values above are based on the table of typic values of % BOD removal vs SALR at the right)**

Slope, SARR/SALR vs SALR: -0.009

Intercept, SARR/SALR vs SALR: 0.989

Est. of SARR/SALR Rato = 0.775

(Surf. Area Removal Rate/Surf. Area Loading Rate)

**3. Parameters for Second Stage:**

Design Value of BOD Surface Area Loading Rate (SALR) = 7.5 g/m²/d

**See information on typical design values for SALR to the right.**

Est. of SARR/SALR Rato = 0.925

(Surf. Area Removal Rate/Surf. Area Loading Rate)

### II. Carrier Parameter and Tank Shape Inputs for both First and Second Stages

Carrier Spec. Surf. Area = 500 m²/m³
(value from carrier mfr/vendor)

Design Carrier Fill % = 40%

**(Carrier fill % is typically between 30% and 70%. Lower values are more conservative, allowing future capacity expansion or reduction of SALR by adding more carrier.)**

Liquid Depth in Tank = 8 ft

Tank L:W ratio = 1.5

**(target L:W - only used if tank is rectangular)**

**Click on green box and then on arrow to Select Tank Shape:** **rectangular**

Carrier % Void Space = 60%

**(from carrier mfr/vendor - only needed to calculate hydraulic detention time)**

**Figure 13.** Screenshot of MBBR Process Design Calculations – Two-Stage BOD Removal – Part 1

## III. Calculation of Carrier Volume and Required Tank Volume & Dimensions

### 1. First Stage Calculations (BOD Removal)

| | | | | | |
|---|---|---|---|---|---|
| BOD Daily Loading = | 300.2 | lb/day | Calculated Tank Volume = | 27.2 | $m^3$ |
| | 136186 | g/day | = | 961.9 | $ft^3$ |
| Carrier Surf. Area needed = | 5447.4 | $m^2$ | = | 7195 | gal |
| Calculated Carrier Volume = | 10.895 | $m^3$ | Calculated Tank Width = | 9.0 | ft |
| Tank Liquid Volume = | 808.0 | $ft^3$ | Calculated Tank Length = | 13.4 | ft |
| | | | Nominal Hydraulic Retention Time at | | |
| Estimate of BOD Surface Area | | | Design Average Flow = | 44 | min |
| Removal Rate, **SARR** = | 19.38 | $g/m^2/d$ | Peak Hourly Flow = | 11 | min |
| Est. of BOD Removal Rate: | 105544 | g/day | | | |
| | 232.7 | lb/day | Calculated Effl BOD Conc.: (from First Stage) | 41 | mg/L |

### 2. Second Stage Calculations (BOD Removal)

| | | | | | |
|---|---|---|---|---|---|
| BOD Daily Loading = | 67.6 | lb/day | Calculated Tank Volume = | 20.4 | $m^3$ |
| | 30642 | g/day | = | 721.4 | $ft^3$ |
| Carrier Surf. Area needed = | 4085.6 | $m^2$ | = | 5396 | gal |
| Calculated Carrier Volume = | 8.171 | $m^3$ | Calculated Tank Width = | 7.8 | ft |
| Tank Liquid Volume = | 606.0 | $ft^3$ | Calculated Tank Length = | 11.6 | ft |
| | | | Nominal Hydraulic Retention Time at | | |
| Estimate of BOD Surface Area | | | Design Average Flow = | 33 | min |
| Removal Rate, **SARR** = | 6.94 | $g/m^2/d$ | Peak Hourly Flow = | 8 | min |
| Est. of BOD Removal Rate: | 28344 | g/day | | | |
| | 62.5 | lb/day | Calculated Effl BOD Conc.: (from Second Stage) | 3.0 | mg/L |

**If the calculated Effl. BOD conc. is too high for eithe stage, the design value of SALR should be reduced for that stage.**

**Figure 14.** Screenshot of MBBR Process Design Calculations – Two-Stage BOD Removal – Part 2

b) For the second stage:

i) The BOD loading rate will be (0.2 MGD)(41 mg/L)(8.34 lb/MG/mg/L) = 67.6 lb/day = (67.6 lb/day)*(453.59 g/lb) = **30,642 g BOD/day**

ii) Required carrier surface area = (30642 g/day)/(7.5 g/$m^2$/day) = 4085.6 $m^2$.

Required carrier volume = 4085.6 $m^2$/500 $m^2/m^3$. = 8.171 $m^3$ = (8.171 $m^3$)(3.2808$^3$ $ft^3/m^3$) = **288.6 $ft^3$**. (**8.171 $m^3$**)

iii) For 40% carrier fill: Required tank volume = 288.55 $ft^3$/0.40 = **721.4 $ft^3$**. (**20.43 $m^3$**)

iv) The volume of liquid in the reactor can be calculated as: tank volume – [carrier volume( 1 – void %)], Thus the volume of liquid is: 721.4 – [288.6(1 – 0.60)] = **606 $ft^3$**. (**17.1 $m^3$**)

v) The HRT at design ave ww flow can be calculated as:
$HRT_{des\ ave}$ = reactor liquid volume*7.48/[Q*$10^6$/(24*60)] = 606*7.48/[0.2*$10^6$/(24*60)] = **33 min**

$HRT_{peak\ hr}$ = $HRT_{des\ ave}$/peak hour factor = 44/4 = **8 min**

Calculation of the estimated effluent BOD concentration from the second stage as shown above for the single stage process gives a value of **3.0 mg/L**.

**Example #6:** Compare the MBBR tank volume, carrier surface area, and estimated effluent BOD concentration for the single stage BOD removal process in **Example #1** and the same WW flow and BOD with a two-stage BOD removal process as calculated in **Example #5**.

**Solution:** The results are summarized below:

| | Single Stage Process | Two Stage Process |
|---|---|---|
| MBBR Volume: | 3206 $ft^3$ | 1683 $ft^3$ |
| Carrier Surf. Area: | 18158 $m^2$ | 9533 $m^2$ |
| Est. Effl. BOD: | 14 mg/L | 3 mg/L |

Note that the two-stage process requires only about half of the tank volume and half of the carrier quantity in comparison with the single stage process, while achieving a significantly lower estimated effluent BOD.

## 8. Two-Stage BOD Removal and Nitrification Process Design Calculations

A two stage MBBR process may also be used to achieve both BOD removal and nitrification. Nitrification with an MBBR process requires a rather low BOD concentration. Thus the first stage for this process is used for BOD removal and the second stage is used for nitrification. A typical flow diagram for a two stage MBBR process for BOD removal and nitrification is shown in **Figure 15** below.

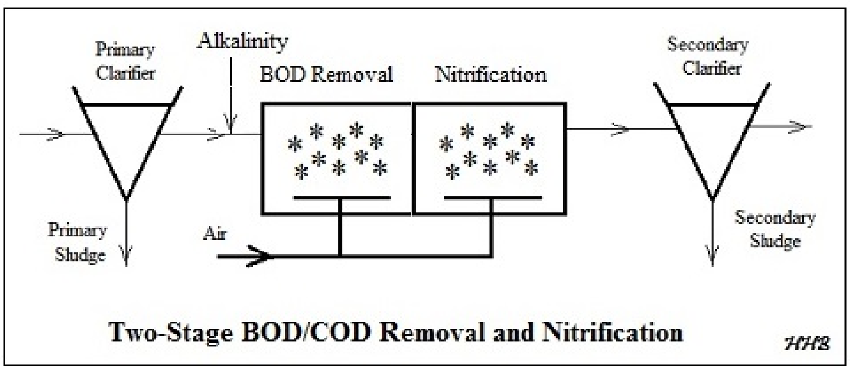



**Figure 15.** Two-Stage MBBR Process for BOD Removal and Nitrification

**Table 3** shows typical design values for the SALR (surface area loading rate) for the BOD removal stage and for the nitrification stage. The source for the values in this table is the Odegaard reference #2 below. The design SALR value for nitrification, however, will be calculated based on the design D.O concentration and the target effluent NH3-N concentration, as it was for the single-stage nitrification process.

**Table 3.** Typical Design SALR Values for Nitrification

| Typical Design Values for MBBR reactors at 15°C | | |
|---|---|---|
| Purpose | Treatment Target % Removal | Design SALR $g/m^2$-d |
| Nitrification | | |
| BOD removal stage | 90 - 95 ($BOD_7$) | 6.0 ($BOD_7$) |
| Effl. $NH_3$-N > 3 mg/L[2] | 90 ($NH_3$-N) | 1.00 ($NH_3$-N) |
| Effl. $NH_3$-N < 3 mg/L[2] | 90 ($NH_3$-N) | 0.45 ($NH_3$-N) |

The process design calculations for the two-stage BOD Removal/Nitrification process would be essentially the same as those just discussed for the two-stage BOD removal process, with the second stage calculations being like those for the single stage nitrification process.

## 9. Introduction to MBBR Denitrification Processes

**Denitrification Background:** In order to carry out denitrification of a wastewater flow (removal of the nitrogen from the wastewater), it is necessary to first nitrify the wastewater, that is, convert the ammonia nitrogen typically present in the influent wastewater to nitrate. As previously noted, nitrification will only take place at a reasonable rate if the BOD level is quite low. Thus, an MBBR denitrification process will need a reactor for BOD removal, one for nitrification, and one for denitrification. The nitrification reactor will always follow the BOD removal reactor, because of the need for a low BOD level in the nitrification reactor. The denitrification reactor may be either before the BOD removal reactor (called pre-anoxic denitrification) or after the nitrification reactor (called post-anoxic denitrification). Flow diagrams for these two denitrification options are shown in **Figure 16** below.

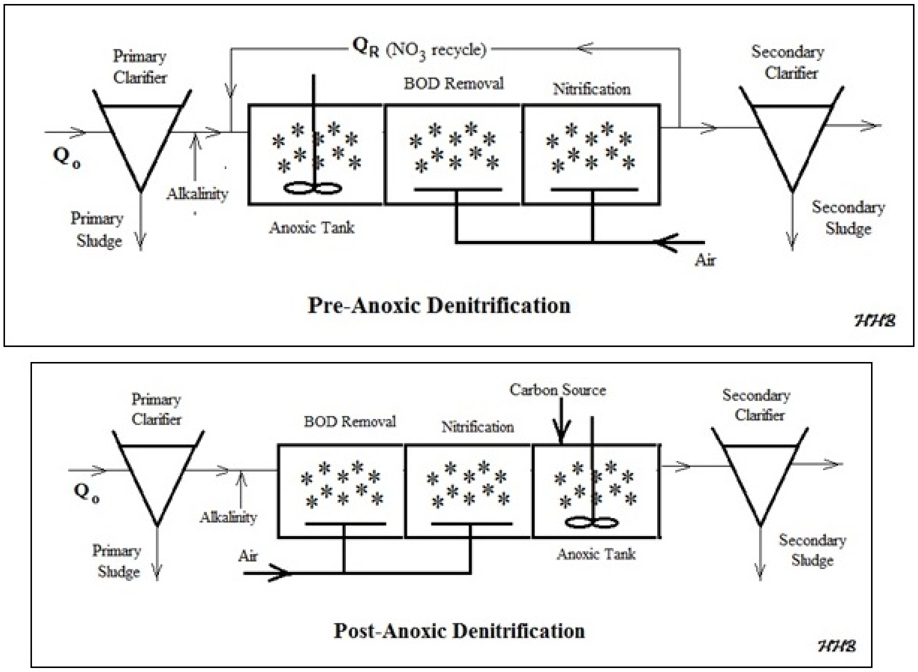



**Figure 16.** MBBR Denitrification Process Alternatives

A bit more information about the denitrification reactions will be useful for further discussion of these two denitrification options. The denitrification reactions, which convert nitrate ion to nitrogen gas, and hence remove it from the wastewater flow, will take place only in the absence of oxygen, that is, in an anoxic reactor. Also, the denitrification reactions require a carbon source. With these factors in mind the functioning of the pre-anoxic denitrification process and of the post-anoxic denitrification process can be described as follows.

In a pre-anoxic denitrification process, the BOD in the primary effluent wastewater is used as the carbon source for denitrification. In this process, however the primary effluent entering the pre-anoxic reactor still has ammonia nitrogen present rather than the nitrate nitrogen needed for denitrification. A recycle flow of effluent from the nitrification reactor is used to send nitrate nitrogen to the denitrification reactor.

In a post-anoxic denitrification process, the influent to the denitrification reactor comes from the nitrification reactor, so the ammonia nitrogen present in the wastewater influent has been converted to nitrate as required for denitrification. The BOD has also been removed prior to the post anoxic denitrification reactor, however, so an external carbon source is required for the denitrification reactions. Methanol is a commonly used carbon source.

**Choosing between Pre-Anoxic and Post-Anoxic Denitrification:** The pre-anoxic denitrification process has the advantage of not requiring an external carbon source and it reduces the BOD load to the BOD removal part of the process because BOD is used in the denitrification reactions. However, the pre-anoxic process requires an influent C/N ratio greater than 4, where C/N is taken to be BOD/TKN, and the post-anoxic process can achieve a more complete nitrogen removal.

From the Odegaard references (#1 and #2 below) suitable criteria for determining whether to use pre- or post-anoxic denitrification are as follows:

1. Pre-anoxic denitrification is suitable if **C/N ≥ 4**
   and **target % Removal of N < 75%**

2. Post-anoxic denitrification should be used if **C/N < 4**
   or **target % Removal of N > 75%**

## 10. Post-Anoxic Denitrification Process Design Calculations

Process design of a post-anoxic denitrification MBBR system, requires sizing an MBBR tank for BOD removal, one for nitrification and one for denitrification. For each of these three reactors the calculations for sizing the reactor are as discussed and illustrated with examples above. A typical flow diagram for a post-anoxic denitrification MBBR process is shown in **Figure 17** below.

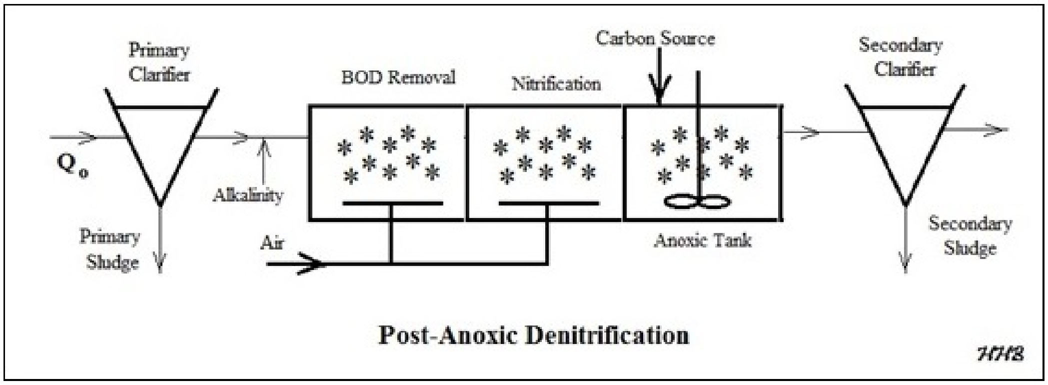



**Figure 17.** Flow Diagram for Post-Anoxic Denitrification

**Example #7:** A design wastewater flow of 0.2 MGD containing 180 mg/L BOD, 35 mg/L TKN, and 140 mg/L alkalinity as $CaCO_3$ (in the primary effluent) is to be treated in a post-anoxic denitrification MBBR process. Carry out the process design for the denitrification stage as described below, using a design SALR of 2 g $NO_3$-N/m$^2$/d.

For the third (Denitrification) stage calculate each of the following:

i) The nitrate loading
ii) The required carrier volume for a carrier with specific surface area of 500 m$^2$/m$^3$
iii) The required MBBR tank volume for a design carrier fill % of 40%
iv) The volume of liquid in the MBBR reactor for design carrier % void space of 60%.
v) The average hydraulic retention time at design average wastewater flow and at design peak hourly flow if the design peak hour factor is 4.
vi) The alkalinity requirement in lb/day as $CaCO_3$ and in lb/day $NaHCO_3$, for target effluent alkalinity of 80 mg/L as $CaCO_3$.
viii) The methanol requirement in lb/day for methanol use as the carbon source.

**Solution:** The nitrate loading to the anoxic reactor will be calculated using (primary clarifier TKN conc. – effluent nitrate conc. from nitrification stage) as the nitrate concentration coming into the post anoxic reactor. Thus, the BOD removal reactor and Nitrification reactor must be designed before the post-anoxic denitrification reactor. The results for those two reactors will be presented and briefly discussed first. Then the calculations for the anoxic stage will be presented.

The calculations for the BOD removal stage would be carried out as described in Examples #1 and #3, using 6.0 g BOD/$m^2$/d as the design SALR based on Table 3, rather than the 7.5 g BOD/$m^2$/d used in Examples #1 & #3. The BOD Daily Loading is the same as that calculated in Example #1, 136,186 g/day or 300.2 lb/day. The required tank size is a bit larger because of the lower design SALR used in this case and the calculated effluent BOD concentration is 12 mg/L rather than the 14 mg/L calculated in Example #1 (with the 7.5 value for SALR). The results for the BOD stage calculations are shown in the Figure 18 spreadsheet screenshot below.

The calculations for the Nitrate removal stage would be carried out exactly the same as described in Example #4 for a single stage nitrate removal process with the same wastewater flow rate, influent TKN, and design SALR (0.63 g $NH_3$-N/$m^2$/d). The results are shown in the Figure 10 spreadsheet screenshot (on page 24), including the specified effluent $NH_3$-N concentration of 3.3 mg/L from this stage.

The calculations for the post-anoxic denitrification stage are as follows. The S.I. version of the spreadsheet can be used with the 0.2 MGD wastewater flow rate specified as 757 $m^3$/d. All of the other inputs remain as given above. The answers in S.I. units (if different than the U.S. solution) are shown in parentheses at the end of each part of the solution below

i) The $NO_3$-N loading rate will be (0.2 MGD)(35 – 3.3 mg/L)(8.34 lb/MG/mg/L) = 52.9 lb/day = (52.9 lb/day)*(453.59 g/lb) = **<u>23,984 g $NO_3$-N/day</u>**

(Note that 35 mg/L is the primary effluent TKN concentration and 3.3 mg/L is the estimated effluent $NH_3$-N concentration.}

ii) Required carrier surface area = (23984 g/day)/(2 g/$m^2$/day) = 11992 $m^2$.

Required carrier volume = 11508 $m^2$/500 $m^2$/$m^3$. = 23.98 $m^3$ = ($23.98\ m^3$)($3.2808^3\ ft^3/m^3$) = **<u>846.9 $ft^3$</u>**. (**23.98 $m^3$**)

**III. Carrier and Tank Shape Parameter Inputs for all Three Stages**

| | | | | | |
|---|---|---|---|---|---|
| Carrier Spec. Surf. Area = | 500 | $m^2/m^3$ | Liquid Depth in Tank = | 8 | ft |
| (from carrier mfr/vendor) | | | Tank L:W ratio = | 1.5 | |
| | | | (target L:W - only used if tank is rectangular) | | |
| Design Carrier Fill % = | 40% | | Click on green box and then on arrow to Select Tank Shape: | rectangular | |
| (Carrier fill % is typically between 30% and 70%. Lower values are more conservative, allowing future capacity expansion or reduction of SALR by adding more carrier.) | | | Carrier % Void Space = | 60% | |
| | | | (from carrier mfr/vendor - only needed to calculate hydraulic detention time) | | |

**IV. Calculation of Carrier Volume and Required Tank Volume & Dimensions**

**1. First Stage (BOD Removal) Calculations**

| | | | | | |
|---|---|---|---|---|---|
| | | | Required Tank Volume = | 113.5 | $m^3$ |
| BOD Daily Loading = | 300.2 | lb/day | | 4007.8 | $ft^3$ |
| BOD Daily Loading = | 136186 | g/day | | 29978 | gal |
| Carrier Surf. Area needed = | 22698 | $m^2$ | Calculated Tank Width = | 18.3 | ft |
| Calculated Carrier Volume = | 45.40 | $m^3$ | Calculated Tank Length = | 27.4 | ft |
| Tank Liquid Volume = | 3366.6 | $ft^3$ | Nominal Hydraulic Retention Time at | | |
| | | | Design Average Flow = | 181 | min |
| Estimate of BOD Surface Area | | | Peak Hourly Flow = | 45.3 | min |
| Removal Rate, **SARR** = | 5.61 | $g/m^2/d$ | Calculated Effl BOD Conc.: | 12 | mg/L |
| Est. of BOD Removal Rate: | 127334 | g/day | If the calculated Effl. BOD conc. Is too high, the design value of SALR (in cell C26) should be reduced. | | |
| | 280.7 | lb/day | | | |

**Figure 18.** Screenshot Post-Anoxic Denitrification Calculations – BOD Removal Stage

iii) For 40% carrier fill: Required tank volume = 846.9 $ft^3$/0.40 = **2117.5 $ft^3$**. (**59.96 $m^3$**)

iv) The volume of liquid in the reactor can be calculated as:
tank volume – [carrier volume( 1 – void %)],   Thus the volume of liquid is:
2117.5 – [846.9(1 – 0.60)]  =  **1778.7 $ft^3$**.         (**50.37 $m^3$**)

v) The HRT at design ave ww flow can be calculated as:
$HRT_{des\ ave}$ = reactor liquid volume*7.48/[Q*$10^6$/(24*60)]  =
1778*7.48/[0.2*$10^6$/(24*60)]  =  **96 min**

$HRT_{peak\ hr}$  =  $HRT_{des\ ave}$/peak hour factor  =  96/4 = **24 min**

These results are shown in the **Figure 19** spreadsheet screenshot below

vi) Calculation of the alkalinity requirement is shown in the **Figure 20** spreadsheet screenshot below. Note that alkalinity is produced in the denitrification reactions, so less alkalinity addition will be needed with denitrification present. Using the equivalent weight of $CaCO_3$ as 50, the equivalent weight of $NaHCO_3$ as 84, the alkalinity use for nitrification as 7.14 g $CaCO_3$/g $NH_3$-N, the alkalinity produced by denitrification as 3.56 g $CaCO_3$/g $NO_3$-H, and the target effluent alkalinity as 80 mg/L as $CaCO_3$, give the calculated alkalinity requirement as 81.9 mg/L as $CaCO_3$.  The rate of alkalinity addition needed can then be calculated as:  (0.2 MGD)(81.9 mg/L)*8.34  =  **136.7 lb/day as $CaCO_3$**.    **(61.9 kg/day as $CaCO_3$)**.     Multiplying this by the ratio of the equivalent weight of $NaHCO_3$ to the equivalent weight of $CaCO_3$ gives the daily $NaHCO_3$ requirement as **229.6 lb/day $NaHCO_3$**.        **(104.1 kg/day as $NaHCO_3$)**

vii) Calculation of the methanol requirement in lb/day is shown at the bottom of the **Figure 20** screenshot.  As shown, the calculations use the constants, 4.6 lb COD/lb $NO_3$-N removed and 1.5 lb COD/lb Methanol.  The required methanol dosage is then calculated as: 4.6/1.5
= 3.1 lb methanol /lb $NO_3$-N removed.  The methanol requirement in lb/day is then equal to 3.1 times the previously calculated $NO_3$-N removal rate of 44.9 lb/day, or **137.8 lb/day**.      **(62.5 kg/day)**

| | | | | | |
|---|---|---|---|---|---|
| **III. Carrier and Tank Shape Parameter Inputs for all Three Stages** | | | | | |
| Carrier Spec. Surf. Area = | 500 | $m^2/m^3$ | **Click on green box and then on** | | |
| (from carrier mfr/vendor) | | | **arrow to Select Tank Shape:** | **rectangular** | |
| Liquid Depth in Tank = | 8 | ft | Carrier % Void Space = | 60% | |
| Tank L:W ratio = | 1.5 | | **(from carrier mfr/vendor - only needed to** | | |
| **(target L:W - only used if tank is rectangular)** | | | **calculate hydraulic detention time)** | | |
| **IV. Calculation of Carrier Volume and Required Tank Volume & Dimensions** | | | | | |
| **3. Third Stage (Post-Anoxic) Calculations** | | | | | |
| Design Carrier Fill % = | 40% | (for third stage) | Required Tank Volume = | 59.96 | $m^3$ |
| $NO_3$-N Daily Loading = | 52.9 | lb/day | Required Tank Volume = | 2117.5 | $ft^3$ |
| $NO_3$-N Daily Loading = | 23984 | g/day | | 15839 | gal |
| Carrier Surf. Area needed = | 11992 | $m^2$ | Calculated Tank Width = | 13.3 | ft |
| Calculated Carrier Volume = | 23.98 | $m^3$ | Calculated Tank Length = | 19.9 | ft |
| Tank Liquid Volume = | 1778.7 | $ft^3$ | Nominal Hydraulic Retention Time at | | |
| Estimate of $NO_3$-N Surface Area | | | Design Average Flow = | 96 | min |
| Removal Rate, **SARR** = | 1.70 | $g/m^2/d$ | Peak Hourly Flow = | 24 | min |
| Est. of $NO_3$-N Removal Rate: | 20386 | g/day | Calculated Effl $NO_3$-N Conc.: | 4.8 | mg/L |
| | 44.9 | lb/day | **If the calculated Effl. $NO_3$-N conc. Is** | | |
| 1st stage tank volume - | | | **too high, the design value of SALR** | | |
| 3rd stage tank volume = | 53.5 | | **(in cell C36) should be reduced.** | | |
| **To make the 3rd stage tank volume the same as the first** | | | | | |
| **stage tank volume, use Excel's Goal Seek process to set** | | | | | |
| **cell C101 equal to zero by changing the value in cell C90.** | | | | | |

**Figure 19.** Post-Anoxic Denitrification Calculations – Anoxic Stage – Part 1

| | | | | | |
|---|---|---|---|---|---|
| **VII. Calculation of Alkalinity Requirements** | | | | | |
| **Input:** Target Effluent Alkalinity = | 80 | mg/L as $CaCO_3$ | | | |
| **Constants needed for Calculations:** | | | | | |
| Equiv Wt. of $CaCO_3$ = | 50 | g/equiv. | Equiv Wt. of $NaHCO_3$ = | 84 | g/equiv. |
| Alkalinity used for Nitrification = | 7.14 | g $CaCO_3$/g $NH_3$-N removed | | | |
| Alkalinity produced by Denitrification = | 3.57 | g $CaCO_3$/g $NO_3$-N removed | | | |
| **Calculations** | | | | | |
| Alkalinity to be added = | 81.9 | mg/L as $CaCO_3$ | | | |
| Daily Alkalinity Requirement = | 136.7 | lb/day as $CaCO_3$ | | | |
| **For sodium bicarbonate use to add alkalinity:** | | | | | |
| Daily $NaHCO_3$ Requirement = | 229.6 | lb/day $NaHCO_3$ | | | |
| **VII. Calculation of Carbon Source Requirements** | | | | | |
| **Inputs:** Carbon Source to be used: | Methanol | | | | |
| COD Requirement for Denitrification = | 4.6 | lb COD/lb $NO_3$-N removed | | | |
| COD Content of Carbon Source = | 1.5 | lb COD/lb Carbon Source | | | |
| **Calculations** | | | | | |
| Carbon Source Dosage = | 3.1 | lb Carbon Source/lb $NO_3$-N removed | | | |
| Daily Carbon Source Requirement = | 137.8 | lb/day | 62.51788514 | | |

**Figure 20.** Post-Anoxic Denitrification Calculations – Anoxic Stage – Part 2

# 11. Pre-Anoxic Denitrification Process Design Calculations

The process design calculations for pre-anoxic denitrification, are similar to those just discussed for a post-anoxic denitrification process. The graph shown in **Figure 21** (prepared using values from a similar graph in Rusten and Paulsrud's presentation in Ref #4 below) will be used to obtain values for SARR/SALR vs SALR for the pre-anoxic denitrification stage.

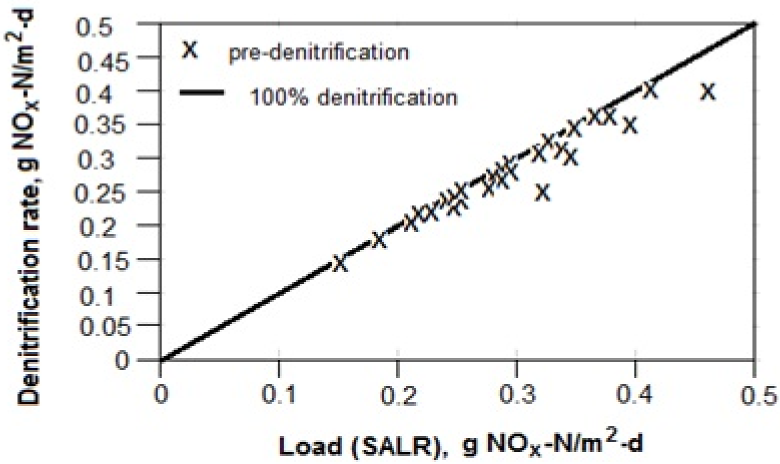



**Figure 21. SARR/SALR** vs **SALR** for Pre-Anoxic Denitrification

A typical flow diagram for a pre-anoxic denitrification MBBR process is shown in **Figure 22** below. As discussed previously for a post-anoxic denitrification MBBR system, process design of a pre-anoxic denitrification MBBR system also requires sizing an MBBR tank for BOD removal, one for nitrification and one for denitrification. Process design for the nitrification stage is essentially the same as just discussed for the post-anoxic denitrification process.

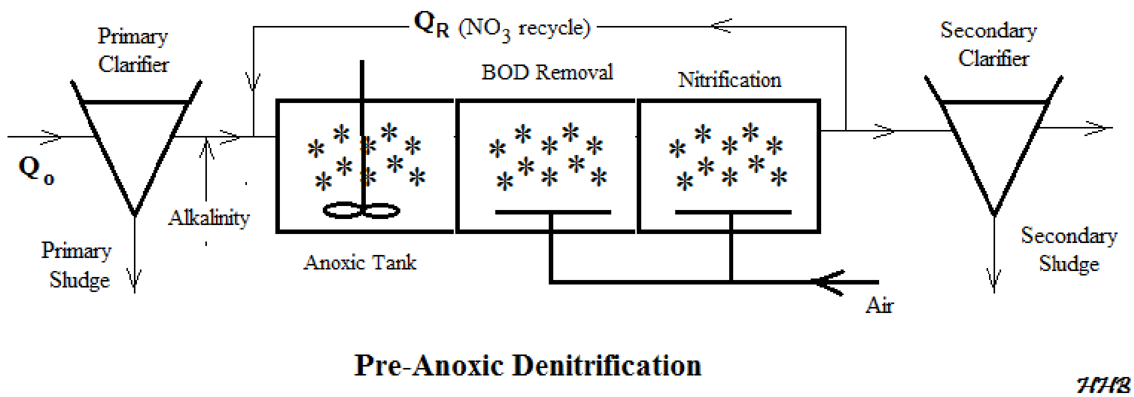



**Figure 22.** MBBR Flow Diagram for Pre-Anoxic Denitrification

Process Design results for the BOD removal stage will be a bit different from those for the BOD removal stage in the post-anoxic process, because some of the incoming BOD will be used as the carbon source in the denitrification reactions in the pre-anoxic tank. For the pre-anoxic process, the BOD loading rate (in lb/day) should be calculated as:

**BOD Daily Loading = (Qo*So*8.34) - (0.67*(20/7)*$NO_3$-N removal rate)**

The second term is the estimated BOD removal rate in the anoxic reactor through its use in the denitrification reactions. This gives a lower BOD loading rate than that for the post-anoxic process with the same primary clarifier effluent coming in. Hence the required tank size for BOD removal will be smaller for the pre-anoxic process.

The main difference from the post-anoxic denitrification process design calculations is for the denitrification stage, which will be discussed and illustrated with **Example #8** calculations below.

**Example #8:** Carry out the process design as described below for the denitrification stage of a pre-anoxic denitrification process with the wastewater flow and concentrations given in Examples #1, #2, and #3. [0.2 MGD containing 180 mg/L BOD and 35 mg/L TKN (in the primary effluent)]. Consider that the primary effluent alkalinity is 140 mg/L as $CaCO_3$ and the design SALR for the denitrification stage is to be 0.9 g $NO_3$-N/$m^2$/d. The nitrification stage was designed for an effluent NH4-N concentration of 3.3 mg/L.

For the first stage (Denitrification) calculate each of the following:

i) The nitrate loading
ii) The required carrier volume for a carrier with specific surface area of 500 $m^2/m^3$
iii) The required MBBR tank volume for a design carrier fill % of 40%
iv) The volume of liquid in the MBBR reactor for design carrier % void space of 60%.
v) The average hydraulic retention time at design average wastewater flow and at design peak hourly flow if the design peak hour factor is 4.
vi) The required $NO_3$-N recycle rate in order to achieve a target $NO_3$-N concentration of 9 mg/L.
vii) The alkalinity requirement in lb/day as $CaCO_3$ and in lb/day $NaHCO_3$, for target effluent alkalinity of 80 mg/L as $CaCO_3$.

**Solution -** The solution is shown in **Figure 23**, **Figure 24**, and **Figure 25**, which are screenshots of different parts of an Excel worksheet used to carry out the calculations for this example. **Figure 23** is from the top part of the worksheet and shows the user inputs and the calculation of the estimated **SARR/SALR** ratio for the denitrification stage. Note also that a user input value is needed for the estimated $NO_3$-N recycle ratio. This initial estimated value is used in an iterative calculation to determine the required $NO_3$-N recycle ratio in order to achieve the target effluent $NO_3$-N concentration.

The S.I. version of the spreadsheet can be used with the 0.2 MGD wastewater flow rate specified as 757 $m^3$/d. All of the other inputs remain as given above. The answers in S.I. units (if different than the U.S. solution) are shown in parentheses at the end of each part of the solution below

**Figure 24** is from the middle of the worksheet and shows the answers for parts i) through vi). The calculations and results are as follows:

i) Most of the nitrate loading to the pre-anoxic denitrification tank is typically in the $NO_3$-N recycle flow rather than in the primary effluent flow entering the tank. The $NO_3$-N loading rate will be (0.2 MGD)(Prim Effl $NO_3$-N)(8.34 lb/MG/mg/L) + (0.2 MGD)(Recycle Ratio)(Target Effl $NO_3$-N)(8.34) = 40.9 lb/day = (40.9 lb/day)*(453.59 g/lb) = **18,534 g $NO_3$-N/day**

ii) Required carrier surface area = (18,534 g/day)/(0.9 g/$m^2$/day) = 20,593 $m^2$.

Required carrier volume = 20,593 $m^2$/500 $m^2/m^3$. = 41.186 $m^3$ = (41.186 $m^3$)($3.2808^3$ $ft^3/m^3$) = **1454 $ft^3$**. (**41.186 $m^3$**)

iii) For 40% carrier fill: Required tank volume = 1454 $ft^3$/0.40 = **3636.2 $ft^3$**. (**103.0 $m^3$**)

iv) The volume of liquid in the reactor can be calculated as:
tank volume – [carrier volume( 1 – void %)], Thus the volume of liquid is:
3636.2 – [1454.4(1 – 0.60)] = **3054.4 ft$^3$**. (**86.49 m$^3$**)

v) The HRT at design ave ww flow can be calculated as:
$HRT_{des\ ave}$ = reactor liquid volume*7.48/[Q*10$^6$/(24*60)] =
3054.4*7.48/[0.2*10$^6$/(24*60)] = **164 min**

$HRT_{peak\ hr}$ = $HRT_{des\ ave}$/peak hour factor = 164/4 = **41 min**

.

vi) The required $NO_3$-N recycle ratio is calculated with the iterative process described in blue in the middle of **Figure 24**. For this iterative process, the $NO_3$-N removal rate is calculated two different ways, one using the estimated SARR and the carrier surface area and the other using the wastewater flow rate times the influent TKN concentration minus the sum of the effluent nitrate and ammonia nitrogen. Excel's Goal Seek process is then used to set the difference between the two different calculations equal to zero by changing the estimated value of the $NO_3$-N recycle ratio. This process results in the required $NO_3$-N recycle ratio calculated to be **2.72**.

viii) Calculation of the alkalinity requirement is shown in the **Figure 25** spreadsheet screenshot. Using the equivalent weight of $CaCO_3$ as 50, the equivalent weight of $NaHCO_3$ as 84, the alkalinity use for nitrification as 7.14 g $CaCO_3$/g $NH_3$-N, the alkalinity produced by denitrification as 3.56 g $CaCO_3$/g $NO_3$-H, and the target effluent alkalinity as 80 mg/L as $CaCO_3$, give the calculated alkalinity requirement as 97.1 mg/L as $CaCO_3$. The rate of alkalinity addition needed can then be calculated as: (0.2 MGD)(91.1 mg/L)*8.34 = **161.9 lb/day as $CaCO_3$**. **(57.3 kg/day as $CaCO_3$)** Multiplying this by the ratio of the equivalent weight of $NaHCO_3$ to the equivalent weight of $CaCO_3$ gives the daily $NaHCO_3$ requirement as **272.0 lb/day $NaHCO_3$**. **(96.2 kg/day as $NaHCO_3$)**

## MBBR Process Design Calculations - U.S. units

### Pre-Anoxic Denitrification Process

**Instructions***: Enter values in blue boxes. Spreadsheet calculates values in yellow boxes*

**I. Wastewater Parameter Inputs**

**1. Parameters for All Three Stages**

| | | | | | |
|---|---|---|---|---|---|
| Design ww Flow Rate, $\mathbf{Q_o}$ = | 0.2 | MGD | Prim. Effl. BOD, $\mathbf{S_o}$ = | 180 | mg/L |
| Prim. Effl. TKN Conc. = | 35 | mg/L | Prim. Effl. $NO_3$-N Conc. = | 0 | mg/L |
| Peak Hour Factor = | 4 | | Prim. Effl. Alkalinity = | 140 | mg/L as $CaCO_3$ |

**2. Parameters for First (Pre-Anoxic) Stage:**

| | | | | | |
|---|---|---|---|---|---|
| | | | Data points for SARR/SALR vs SALR | | |
| Target Effl. $NO_3$-N Conc. = | 9 | mg/L | **SALR** ($g/m^2/d$): | 0.2 | 0.5 |
| Est. of $NO_3$-N Recycle Ratio: | 2.72 | | **SARR/SALR:** | 0.95 | 0.94 |
| **($Q_R/Q_o$) - An estimate is needed here to start the iterative calculation in Sec IV below** | | | **(default values above are from a graph of Pre-Anoxic SARR vs SALR in ref #6 below right)** | | |
| | | | **(The graph is shown at the right.)** | | |
| Design Value of $NO_3$-N Surface Area Loading Rate (SALR) = | 0.9 | $g/m^2/d$ | Slope, SARR/SALR vs SALR: | | -0.033 |
| **See information on typical design values for SALR at right.** | | | Intercept, SARR/SALR vs SALR: | | 0.957 |
| | | | Est. of SARR/SALR Rato = | | 0.927 |
| | | | (Surf. Area Removal Rate/Surf. Area Loading Rate) | | |

**3. Parameters for Second (BOD Removal) Stage:**

| | | | | | |
|---|---|---|---|---|---|
| | | | Data points for SARR/SALR vs SALR (for BOD7) | | |
| Design Value of BOD Surface | | | **SALR** ($g/m^2/d$): | 7.5 | 15.0 |
| Area Loading Rate (SALR) = | 6 | $g/m^2/d$ | **SARR/SALR:** | 0.925 | 0.875 |
| **See information on typical design values for SALR at right.** | | | **(default values above are from the table of typical values of % BOD7 removal vs SALR shown at the right from ref #2)** | | |
| Est. of SARR/SALR Rato = | 0.935 | | Slope, SARR/SALR vs SALR: | | -0.007 |
| (Surf. Area Removal Rate/Surf. Area Loading Rate) | | | Intercept, SARR/SALR vs SALR: | | 0.975 |

**4. Parameters for Third (Nitrification) Stage:**

| | | | | | |
|---|---|---|---|---|---|
| Min Design Temp., **T** = | 45 | °F | Target Effl $NH_4$-N Conc, $\mathbf{NH_4\text{-}N_e}$ = | 3.3 | mg/L |
| | | | **Click on cell H26 and on arrow to select D.O Conc.** | | |
| | | | D.O Conc. in Reactor = | 3.0 | mg/L |

**5. Preliminary Calculations - Design SALR value for Nitrification**

| | | | | | |
|---|---|---|---|---|---|
| % $NH_4$-N removal = | 91% | | $NH_4$-$N_e$ @ $SARR_{max}$ = | 0.80 | mg/L |
| Maximum SARR = | 0.88 | $g/m^2/d$ | SARR @ $NH_4$-Ne, 15°C, $\mathbf{SARR_{15}}$ = | 0.88 | $g/m^2/d$ |
| | | | SARR @ $NH_4$-Ne, T °C, $\mathbf{SARR_T}$ = | 0.57 | $g/m^2/d$ |
| SARR Temp. Coeff, **θ** = | 1.058 | | Design Value for nitrification **SALR** = | 0.63 | $g/m^2/d$ |

**Figure 23.** Screenshot – Pre-Anoxic Denitrification Design Calculations – Part 1

**III. Carrier and Tank Shape Parameter Inputs for all Three Stages**

| | | | | |
|---|---|---|---|---|
| Carrier Spec. Surf. Area = | 500 | $m^2/m^3$ | Click on green box and then on | |
| (from carrier mfr/vendor) | | | arrow to Select Tank Shape: | rectangular |
| Liquid Depth in Tank = | 8 | ft | Carrier % Void Space = | 60% |
| Tank L:W ratio = | 1.5 | | (from carrier mfr/vendor - only needed to | |
| (target L:W - only used if tank is rectangular) | | | calculate hydraulic detention time) | |

**IV. Calculation of Carrier Volume and Required Tank Volume & Dimensions**

**1. First Stage (Pre-Anoxic Tank) Calculations**

(Carrier fill % is typically between 30% and 70%. Lower values are more conservative, allowing future capacity expansion or reduction of SALR by adding more carrier.

| | | | | | |
|---|---|---|---|---|---|
| Design Carrier Fill % = | 40% | (for first stage) | | | |
| $NO_3$-N Daily Loading = | 40.9 | lb/day | Calculated Tank Volume = | 103.0 | $m^3$ |
| $NO_3$-N Daily Loading = | 18533.7 | g/day | | 3636.2 | $ft^3$ |
| Carrier Surf. Area needed = | 20593.0 | $m^2$ | | 27199 | gal |
| Calculated Carrier Volume = | 41.186 | $m^3$ | Calculated Tank Width = | 17.4 | ft |
| Tank Liquid Volume = | 3054.4 | $ft^3$ | Calculated Tank Length = | 26.1 | ft |
| | | | Nominal Hydraulic Retention Time at | | |
| Estimate of $NO_3$-N Surface Area | | | Design Average Flow = | 164 | min |
| Removal Rate, **SARR** = | 0.83 | $g/m^2/d$ | Peak Hourly Flow = | 41 | min |
| Req'd $NO_3$-N Removal Rate: | 37.86 | lb/day | Est. of $NO_3$-N Removal Rate: | 37.86 | g/day |
| (for Effl. $NO_3$-N = Target Value) | | | Est. Rem Rate - Req'd Rate: | 0.0000 | g/day |

**NOTE: Use Excel's "Goal Seek" to find $Q_R/Q_o$ as follows: Place the cursor on cell H73 and click on "Goal Seek" (in the "tools" menu of older versions and under "Data - What if Analysis" in newer versions of Excel). Enter values to "Set cell:" H73, "To value:" 0, "By changing cell:" c17, and click on "OK". The calculated value of $Q_R/Q_o$ will appear in cell C17 and cell H73 should equal zero if the process worked properly. Note that an initial estimate of $Q_R/Q_o$ is needed in cell C17 to start the iterative process.**

**Figure 24.** Screenshot – Pre-Anoxic Denitrification Design Calculations – Part 2

| | | | | | |
|---|---|---|---|---|---|
| **VII. Calculation of Alkalinity Requirements** | | | | | |
| **Input:** | Target Effluent Alkalinity = | 80 | mg/L | | |
| **Constants needed for Calculations:** | | | | | |
| Equiv Wt. of $CaCO_3$ = | 50 | g/equiv. | Equiv Wt. of $NaHCO_3$ = | 84 | g/equiv. |
| Alkalinity used for Nitrification = | 7.14 | g $CaCO_3$/g $NH_3$-N removed | | | |
| Alkalinity produced by Denitrification = | 3.57 | g $CaCO_3$/g $NO_3$-N removed | | | |
| **Calculations** | | | | | |
| Alkalinity to be added = | 97.1 | mg/L as $CaCO_3$ | | | |
| Daily Alkalinity Requirement = | 161.9 | lb/day as $CaCO_3$ | | | |
| **For sodium bicarbonate use to add alkalinity:** | | | | | |
| Daily $NaHCO_3$ Requirement = | 272.0 | lb/day $NaHCO_3$ | | | |

**Figure 25.** Screenshot – Pre-Anoxic Denitrification Design Calculations – Part 3

# 12. Summary

The MBBR (moving bed biofilm reactor) process is an attached growth process that uses plastic carriers to provide a surface on which biofilm grows. The plastic carriers are kept suspended in the aeration tank by an aerator for an aerobic process or by mechanical mixing for an anoxic or anaerobic process. The plastic carriers are kept in the system by a sieve at the outlet of the tank. The MBBR process doesn't require sludge recycle, because the biomass remains in the system attached to the plastic carrier. The required reactor size for an MBBR process is typically significantly smaller than for an activated sludge process treating the same wastewater flow, or for other common attached growth processes like the RBC or trickling filter. It can be used for BOD removal, biological nitrification, biological denitrification, and biological phosphorus removal.

This course provides discussion of and detailed examples of process design calculations for a single stage BOD removal MBBR system, a single stage tertiary nitrification MBBR system, a two-stage BOD removal MBBR system, a post-anoxic denitrification MBBR system and a pre-anoxic denitrification MBBR system.

## 14. References

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