Biological Wastewater Treatment Processes II: MBBR Processes

Course No: C04-045
Credit: 4 PDH

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1. **Introduction**

Biological wastewater treatment is very widely used for removal of biodegradable materials from wastewater. The first course (Part I) of this series, Biological Wastewater Treatment I – Activated Sludge, starts with a discussion of the biochemical oxygen demand that is created by biodegradable materials in water and the reason why such materials must be removed from wastewater. This course (Part II) of this series is about the Moving Bed Biofilm Reactor (MBBR) wastewater treatment process, including background information about the process and a description of the process, as well as process design calculations for several different configurations of the MBBR process and numerous example calculations.

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 components and general configuration of an MBBR wastewater treatment process
- Be able to calculate the loading rate of a wastewater constituent to an MBBR process (in lb/day and g/day) for a specified wastewater flow rate and constituent concentration
- Be able to calculate the required carrier surface area for an MBBR wastewater treatment process for a 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 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. Description of the MBBR (Moving Bed Biofilm Reactor) Process
   
   II. Single Stage BOD Removal MBBR Process Design Calculations
   
   III. Two-Stage BOD Removal MBBR Process Design Calculations
   
   IV. Single Stage Nitrification MBBR Process Design Calculations
   
   V. Two-Stage BOD Removal and Nitrification MBBR Process Design Calculations
   
   VI. Denitrification Background Information
   
   VII. Post-Anoxic Denitrification MBBR Process Design Calculations
   
   VIII. Pre-Anoxic Denitrification MBBR Process Design Calculations

4. **Description of the MBBR (Moving Bed Biofilm Reactor) Process**

   **Initial Development of the MBBR Process:** The MBBR process for wastewater treatment was invented and initially developed by Professor Hallvard Ødegaard in the late 1980s at the Norwegian University of Science and Technology. Use of this wastewater treatment process has spread rapidly. Per Ødegaard, 2014 (Reference #1 at the end of this course), there were already more than 800 MBBR wastewater treatment plants in
more than 50 countries in 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 MBBR 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 (described in more detail in the next section) upon which the microorganisms are attached. 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 illustrated in the figures below. A sieve is typically used at the MBBR 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, because an adequate microorganism population is maintained attached to the media.
The MBBR Media Support Carrier System: MBBR processes use plastic media support carriers similar to those shown in the figure below. As shown in that 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 the figure 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 $\text{m}^2/\text{m}^3$ and the void ratio. The specific surface area of MBBR carriers is typically in the range from 350 to 1200 $\text{m}^2/\text{m}^3$ 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.

MBBR Wastewater Treatment Process Alternatives: The MBBR wastewater treatment process is quite flexible and can be used in several different ways. The figure below shows flow diagrams for the following six alternatives. Note that, as previously mentioned, primary clarification and secondary clarification are shown for all of the process alternatives, but there is no sludge recycle as in a conventional activated sludge process.

1. Single stage BOD removal
2. Two stage BOD removal
3. Two stage BOD removal and Nitrification
4. Single stage tertiary Nitrification
5. Pre-Anoxic Denitrification
6. Post-Anoxic Denitrification
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/m²/d. The g/d in the SALR units refers to the g/d of the parameter being removed and the m² 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 m² of carrier surface area. For a nitrification reactor, the SALR would be g NH₃-N/day entering the MBBR tank per m² of carrier surface area. Finally, for denitrification design, the SALR would be g NO₃-N/day per m² 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 (m²/m³). 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 above will be covered in the next several sections.

5. Single Stage BOD Removal MBBR 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/m²/day, that is g/day of BOD coming into the MBBR tank per m² 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/m²/day gives the required carrier surface area in m². 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 process for BOD removal is shown in the figure below.

The equations for making those calculations are as follows:

1. **BOD loading rate** = \( Q \cdot S_0 \cdot 8.34 \cdot 453.59 \)
   where: \( Q \) is the wastewater flow rate into the MBBR reactor in MGD
   \( S_0 \) 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 surf. area** = \( \frac{\text{BOD Loading Rate}}{\text{SALR}} \)
   where: \( \text{BOD Loading Rate} \) is in g/day
   \( \text{SALR} \) is the design surface area loading rate in g/m²/day
   The calculated **required carrier surface area** will be in m².

3. **required carrier volume** = \( \frac{\text{required carrier surf. area}}{\text{carrier specific surf. area}} \)
   where: \( \text{required carrier surface Area} \) is in m²
carrier specific surface Area is in m²/m³
The calculated required carrier volume will be in m³.

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 m³ can be converted to ft³ by multiplying by 3.2808³ ft³/m³.

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 calculating HRT are as follows:

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

where: liquid vol. in tank is in ft³

Q is in MGD
7.48 is the conversion factor for ft³ 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 below shows typical SALR design values for BOD removal in MBBR reactors. Reference #2 at the end of this course (Ødegaard, 1999) is the source for the values in the table.
Example #1: A design wastewater flow of 1.5 MGD containing 175 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 would be a suitable design SALR to use for a target of 90-95% removal?
c) If the MBBR carrier has a specific surface area of 600 m²/m³ 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 \((1.5\text{ MGD})(175\text{ mg/L})(8.34\text{ lb/MG/mg/L}) = 2189\text{ lb/day}) = (2189\text{ lb/day})*(453.59\text{ g/lb}) = 993,000\text{ 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/m²/day

c) Required carrier surface area = \((993,000\text{ g/day})/(7.5\text{ g/m²/day}) = 132,403\text{ m²}.
Required carrier volume = 132,403\text{ m²}/600\text{ m²/m³} = 220.7\text{ m³}\)

For 40% carrier fill: Required tank volume = 220.7 m³/0.40 = 551.7 m³.

d) The volume of liquid in the reactor can be calculated as:
tank volume – [carrier volume( 1 – void %)]. Thus the volume of liquid is:
\(551.7 – [220.7(1 – 0.60)] = 463.4\text{ m³} = 463.3\text{ m³}(3.28083) = 16,365\text{ ft³}\)
e) The HRT at design average flow can be calculated as:

\[
HRT_{\text{ave}} = \frac{\text{reactor liquid volume} \times 7.48}{[Q \times 10^6/(24 \times 60)]} = 16,365 \times 7.48/[1.5 \times 10^6/(24 \times 60)] = 118 \text{ min}
\]

\[
HRT_{\text{peak hr}} = \frac{HRT_{\text{ave}}}{\text{peak hour factor}} = \frac{118}{4} = 29 \text{ min}
\]

Use of an Excel Spreadsheet: The type of calculations just discussed can be done conveniently using an Excel spreadsheet. The screenshot on the next page shows an example Excel spreadsheet set up to make the calculations as just described for Example #1.

The worksheet shown in the screenshot is set up for user input values to be entered in the blue cells with the values in the yellow cells 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 selects “rectangular” for the tank shape, the worksheet calculates the tank length and width for the calculated required tank volume. If the user selects cylindrical as the tank shape, the worksheet will calculate the tank diameter. These calculations simply use the formulas for the volume of a rectangular tank (\(V = L \times W \times H\)) 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. The effluent BOD calculation is discussed in the next section.

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.
# 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

<table>
<thead>
<tr>
<th>Design ww Flow Rate, Q (MGD)</th>
<th>1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prim. Eff. BOD, S₀ (mg/L)</td>
<td>175</td>
</tr>
<tr>
<td>Peak Hour Factor</td>
<td>4</td>
</tr>
</tbody>
</table>

Data points for SARR/SALR vs SALR:

<table>
<thead>
<tr>
<th>SALR (g/m²/d)</th>
<th>SARR/SALR</th>
<th>Est. of SARR/SALR Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>0.925</td>
<td>-0.007</td>
</tr>
<tr>
<td>15.0</td>
<td>0.875</td>
<td>0.925</td>
</tr>
</tbody>
</table>

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

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

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

<table>
<thead>
<tr>
<th>Surf. Area Removal Rate</th>
<th>Surf. Area Loading Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>(for SALR value specified at left)</td>
<td></td>
</tr>
</tbody>
</table>

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

**Inputs**

<table>
<thead>
<tr>
<th>Carrier Spec. Surf. Area (m²/m³)</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Fill %</td>
<td>40%</td>
</tr>
<tr>
<td>Liquid Depth in Tank ft</td>
<td>8</td>
</tr>
<tr>
<td>Tank L/W ratio</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*(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.)*

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

<table>
<thead>
<tr>
<th>Carrier % Void Space</th>
<th>60%</th>
</tr>
</thead>
</table>

Calculations

<table>
<thead>
<tr>
<th>BOD Daily Loading (lb/day)</th>
<th>2189</th>
</tr>
</thead>
<tbody>
<tr>
<td>g/day</td>
<td>993,022</td>
</tr>
<tr>
<td>Calculated Tank Volume m³</td>
<td>551.7</td>
</tr>
<tr>
<td>ft³</td>
<td>19,482</td>
</tr>
<tr>
<td></td>
<td>145,723</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carrier Surf. Area needed m²</th>
<th>132,403</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated Carrier Volume m³</td>
<td>220.7</td>
</tr>
<tr>
<td>Calculated Tank Width ft</td>
<td>40.3</td>
</tr>
<tr>
<td>Calculated Tank Length ft</td>
<td>60.4</td>
</tr>
</tbody>
</table>

| Tank Liquid Volume ft³        | 16,365  |
| Design Average Flow min       | 118     |
| Peak Hourly Flow min          | 29      |
| Nominal Hydraulic Retention Time at min | 463,4102 16364.58 |

<table>
<thead>
<tr>
<th>Estimate of BOD Surface Area Removal Rate, SARR (g/m²/d)</th>
<th>6.94</th>
</tr>
</thead>
<tbody>
<tr>
<td>Est. of BOD Removal Rate g/day</td>
<td>918.545</td>
</tr>
<tr>
<td>Calculated Eff. BOD Conc. mg/L</td>
<td>13</td>
</tr>
<tr>
<td>lb/day</td>
<td>2026.1</td>
</tr>
</tbody>
</table>

If the calculated Eff. BOD conc. is too high, the design value of SALR (in cell C13) should be reduced.
Based on graphs and tables provided in several of the references at the end of this document, the SARR/SALR ratio for all of 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 page 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:

\[
\text{BOD removal rate in g/day} = (\text{SARR in g/m}^2/\text{d})(\text{Carrier Surf. Area in m}^2)
\]
\[
\text{BOD rate into plant in g/day} = (\text{SALR in g/m}^2/\text{d})(\text{Carrier Surf. Area in m}^2)
\]
\[
\% \text{ BOD removal} = \left( \frac{\text{BOD removal rate}}{\text{BOD rate into plant}} \right) \times 100\%
\]
\[
= (100\%) \frac{(\text{SARR} \times \text{Carrier Surf Area})}{(\text{SALR} \times \text{Carrier Surf Area})}
\]
\[
= (\text{SARR}/\text{SALR})100\%
\]

Thus, the value of 0.925 for the SARR/SALR ratio at SALR = 7.5 g/m²/d was obtained from Table 1 above as the midpoint of the 90-95% estimated % BOD removal for SALR = 7.5 g/m²/d. Similarly, the value of 0.875 for the SARR/SALR ratio at SALR = 15 g/m²/d was obtained from Table 1 above as the midpoint of the 85-90% estimated % BOD removal for SALR = 15 g/m²/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. 
   \[ \text{Est effluent BOD conc.} = \frac{((\text{BOD loading rate} - \text{estimated BOD removal rate})/Q_o)/8.34}{8.34} \]

**Example #2:** 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 spreadsheet screenshot that was used for the solution to **Example #1** above. The pair of points for SARR/SALR vs SALR that were discussed above and are shown on the screenshot lead to the following values for the slope and intercept for the SARR/SALR vs SALR line: \text{Slope} = -0.007, \text{Intercept} = 0.975.

Thus the estimated SARR/SALR ratio for the given SALR value of 7.5 g/m²/d would be calculated as: \text{SARR/SALR} = -(0.007)(7.5) + 0.975 = 0.925

The SARR value can be calculated as:

\[ \text{SARR} = \text{SARR/SALR} \times \text{SALR} = (0.925)(7.5) = 6.94 \text{ g/m}^2/\text{d} \]

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

\[ \text{Est BOD removal rate} = \text{est SARR} \times \text{carrier surface area} = (6.94 \text{ g/m}^2/\text{d})(132,403 \text{ m}^2) = 918,545 \text{ g/d} = 918,545/453.59 \text{ lb/day} \]

\[ \text{Est BOD removal rate} = 2025.1 \text{ lb/day} \]

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

\[ \text{Est effluent BOD conc.} = \frac{((\text{BOD loading rate} - \text{est BOD removal rate})/Q_o)/8.34}{8.34} \]

Substituting calculated and given values:

\[ \text{Est. effluent BOD conc.} = \frac{([2189 - 2026.1]/1.5)/8.34}{8.34} = 13 \text{ mg/L} \]

Note that this 13 mg/L value for the estimated effluent BOD concentration is shown near the bottom of the spreadsheet screenshot.

6. **Two-Stage BOD Removal MBBR 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 the figure below.

Two Stage MBBR Process for BOD/COD Removal

The process design calculations for a two stage MBBR process are essentially the same for each of the stages as for the single stage process, as described in the previous section. These calculations are illustrated in Example #3.

Example #3: A design wastewater flow of 1.5 MGD containing 175 mg/L BOD (in the primary effluent) is to be treated for BOD removal in a two-stage MBBR reactor. The SALR for the first stage is to be 25 g/m²/d and the design SALR for the second stage is to be 7.5 g/m²/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 600 m²/m³
   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 the next two figures below. The first screenshot below 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 second screenshot figure below 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

\[
(1.5 \text{ MGD})(175 \text{ mg/L})(8.34 \text{ lb/MG/mg/L}) = 2189 \text{ lb/day} = (2189 \text{ lb/day})*(453.59 \text{ g/lb}) = 993,022 \text{ g BOD/day}
\]

ii) Required carrier surface area = \(993,022 \text{ g/day})/(25 \text{ g/m}^2/\text{day}) = 39,721 \text{ m}^2\). Required carrier volume = \(39,721 \text{ m}^2/600 \text{ m}^2/\text{m}^3 = 66.20 \text{ m}^3\)

iii) For 40% carrier fill: Required tank volume = \(66.2 \text{ m}^3/0.40 = 165.5 \text{ m}^3\)

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

\[
\text{tank volume} - \text{[carrier volume}(1 - \text{ void %})], \quad \text{Thus the volume of liquid is:} \\
165.5 - [66.20(1 - 0.60)] = 139.02 \text{ m}^3 = 139.02(3.28083) = 4910 \text{ ft}^3
\]

v) The HRT at design ave ww flow can be calculated as:

\[
\text{HRT}_{\text{des ave}} = \frac{\text{reactor liquid volume}*7.48}{[Q*10^6/(24*60)]} = 4910*7.48/[1.5*10^6/(24*60)] = 35 \text{ min}
\]

\[
\text{HRT}_{\text{peak hr}} = \frac{\text{HRT}_{\text{des ave}}/\text{peak hour factor}}{35/4 = 9 \text{ min}}
\]

vi) Calculation of the estimated effluent BOD concentration from the first stage as shown above for the single stage process gives a value of 39 mg/L.

b) For the second stage:

i) The BOD loading rate will be

\[
(1.5 \text{ MGD})(39 \text{ mg/L})(8.34 \text{ lb/MG/mg/L}) = 492.6 \text{ lb/day} = (492.6 \text{ lb/day})*(453.59 \text{ g/lb}) = 223,430 \text{ g BOD/day}
\]

ii) Required carrier surface area = \(223,430 \text{ g/day})/(7.5 \text{ g/m}^2/\text{day}) = 29,791 \text{ m}^2\). Required carrier volume = \(29,791 \text{ m}^2/600 \text{ m}^2/\text{m}^3 = 49.65 \text{ m}^3\)

iii) For 40% carrier fill: Required tank volume = \(49.65 \text{ m}^3/0.40 = 124.1 \text{ m}^3\)

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

\[
\text{tank volume} - \text{[carrier volume}(1 - \text{ void %})], \quad \text{Thus the volume of liquid is:} \\
124.1 - [49.65(1 - 0.60)] = 104.3 \text{ m}^3 = 104.3(3.28083) = 3682 \text{ ft}^3
\]

v) The HRT at design ave ww flow can be calculated as:
HRT_{des \ ave} = \frac{\text{reactor liquid volume} \times 7.48}{[Q \times 10^6/(24 \times 60)]} = 3682 \times \frac{7.48}{[1.5 \times 10^6/(24 \times 60)]} = 26 \text{ min}

HRT_{peak \ hr} = \frac{HRT_{des \ ave}}{\text{peak hour factor}} = \frac{26}{4} = 7 \text{ min}

Calculation of the estimated effluent BOD concentration from the second stage using the calculation procedure shown above for the single stage process gives a value of 3.0 mg/L.
### Example #4:

Compare the MBBR tank volume, carrier surface area, and estimated effluent BOD concentration for the single stage BOD removal process in Example #1 with the two-stage BOD removal process treating the same wastewater flow and influent BOD concentration as calculated in Example #3.
Solution: The results are summarized below:

<table>
<thead>
<tr>
<th></th>
<th>Single Stage Process</th>
<th>Two-Stage Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBBR Volume:</td>
<td>19,482 ft³</td>
<td>10,228 ft³</td>
</tr>
<tr>
<td>Carrier Surf. Area:</td>
<td>132,403 m²</td>
<td>69,512 m²</td>
</tr>
<tr>
<td>Est. Effl. BOD:</td>
<td>13 mg/L</td>
<td>3 mg/L</td>
</tr>
</tbody>
</table>

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.

7. Single Stage Nitrification MBBR Process Design Calculations

An MBBR single stage 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 the figure below. As shown on the diagram, the BOD level should be low enough so that the BOD load to the nitrification process is less than 0.5 g/m²/day. Note that alkalinity is used in the nitrification process and thus alkalinity addition is typically required.

![Single Stage MBBR Process for Nitrification](image)

The process design calculations for this single stage MBBR process are similar to those used for the BOD removal processes, but the design SALR value for nitrification can be calculated rather than being selected 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. The figure 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:

\[ SARR = \left[ \frac{N_e}{2.2 + N_e} \right] \times 3.3, \quad N_e = \text{effluent ammonia N conc.} \]

This is the equation for the curved portion at the left in the graph below, which is for ammonia N concentration limiting conditions.

The horizontal lines in the figure above show the nitrification SARR under D.O. limiting conditions for each of the D.O. levels shown. The SARR will be D.O. limited when the NH₃-N concentration is above the value at the left end of the horizontal line for each D.O. level. When the NH₃-N concentration is below that value, then the SARR is ammonia concentration limited and the SARR is a function of the effluent NH₃-N concentration (\( N_e \)) per the equation: 

\[ SARR = \left[ \frac{N_e}{2.2 + N_e} \right] \times 3.3. \]
As shown in Section 5 for BOD removal, \( \text{SALR/SARR} = \% \text{ BOD removal} \). Similarly, for nitrification, \( \text{SALR/SARR} = \% \text{ NH}_3\text{-N removal} \). After the SARR has been determined, the SALR can be calculated as: \( \text{SALR} = \text{SARR}/\% \text{ removal} \).

The maximum SARR for each of the D.O. levels shown in the figure above 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 \( \text{SARR}_{\text{max}} \) and \( \text{NH}_3\text{-N}_{\text{e}} \) @ \( \text{SARR}_{\text{max}} \)**

<table>
<thead>
<tr>
<th>D.O. (mg/L)</th>
<th>SARR(_{\text{max}}) (g/m(^2)/d)</th>
<th>( \min \text{ NH}<em>3\text{-N}</em>{\text{e}} ) @ SARR(_{\text{max}}) (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.61</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.88</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>1.03</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1.23</td>
<td>1.3</td>
</tr>
<tr>
<td>6</td>
<td>1.41</td>
<td>1.65</td>
</tr>
</tbody>
</table>

**Example #5:** A design flow of 0.2 MGD has the following characteristics: 15 mg/L BOD, 25 mg/L NH\(_3\)-N, 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\(^\circ\)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 600 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\(_3\) for a target effluent alkalinity of 80 mg/L.
Solution:

The solution is shown in the spreadsheet screenshots below. A summary of the calculations is as follows:

a) The D.O. limited SARR can be obtained as $SARR_{\text{max}}$ 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: $SARR_{\text{max}} = 0.88 \text{ g/m}^2/\text{d}$ and minimum $\text{NH}_3-N$ for that value of $SARR_{\text{max}} = 0.80 \text{ mg/L}$. (In the worksheet shown in the first screenshot below, 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°C will then be equal to $SARR_{\text{max}}$ 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°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: $SARR_{\text{T}} = SARR_{15\circ\text{C}} \theta (T - 15)$, where the WW temperature must be in °C. Since this case has D.O. limited conditions, $\theta = 1.058$. Carrying out this calculation gives: design value of SALR = $0.65 \text{ g/m}^2/\text{d}$.

b) The ammonia nitrogen loading rate will be $(0.2 \text{ MGD})(25 \text{ mg/L})(8.34 \text{ lb/MG/mg/L}) = 41.7 \text{ lb/day} = (41.7 \text{ lb/day})*(453.59 \text{ g/lb}) = 18,915 \text{ g NH}_3-\text{N/day}$

c) Required carrier surface area = $(18,915 \text{ g/day})/(0.65 \text{ g/m}^2/\text{day}) = 28,925 \text{ m}^2$.

Required carrier volume = $28,925 \text{ m}^2/600 \text{ m}^2/\text{m}^3 = 48.209 \text{ m}^3$

= $(48.209 \text{ m}^3)(3.28083 \text{ ft}^3/\text{m}^3) = 1702 \text{ ft}^3$.

For 40% carrier fill: Required tank volume = $1702 \text{ ft}^3/0.40 = 4256 \text{ ft}^3$.

d) The BOD SALR will be $(0.2 \text{ MGD})(15 \text{ mg/L})(8.34 \text{ lb/MG/mg/L})(453.59)/(28925 \text{ m}^2)$ = $0.39 \text{ g/m}^2/\text{day}$ (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: $4256 - [1702(1-0.60)] = 3575 \text{ ft}^3$. 

f) The HRT at design average wastewater flow can be calculated as:
\[ HRT_{\text{des ave}} = \frac{\text{reactor liquid volume} \times 7.48}{Q \times 10^6 /[24 \times 60]} \]
\[ = \frac{3575 \times 7.48}{0.2 \times 10^6 /[24 \times 60]} = \textbf{193 min} \]

\[ HRT_{\text{peak hr}} = \frac{HRT_{\text{des ave}}}{\text{peak hour factor}} = \frac{193}{4} = \textbf{48 min} \]

g) Calculation of the alkalinity requirement is shown in the second screenshot below. The alkalinity needed for nitrification is 7.14 g CaCO₃/g NH₃-N removed. Thus, the alkalinity to be added in mg/L can be calculated as:

\[ 7.14(\text{mg/L NH}_3\text{-N removed}) + \text{target effl. Alkalinity} - \text{influent alkalinity} \]

For the given input values, this becomes:

\[ 7.14(25 - 3.3) + 80 - 140 = \textbf{94.9 mg/L as CaCO}_3 \]

The rate of alkalinity addition needed can then be calculated as:

\[ (0.2 \text{ MGD})(94.9 \text{ mg/L}) \times 8.34 = \textbf{158.4 lb/day as CaCO}_3. \]

Multiplying this by the ratio of the equivalent weight of NaHCO₃ (84) to the equivalent weight of CaCO₃ (50) gives the daily NaHCO₃ requirement as:

\[ \textbf{266.0 lb/day NaHCO}_3. \]
# MBBR Process Design Calculations - U.S. units

## Single Stage Tertiary Nitrification Process

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

<table>
<thead>
<tr>
<th>1. General Inputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Hour Factor</td>
<td>4</td>
</tr>
<tr>
<td>Target Eff. NH₄-N Conc., NH₄-Nₑ</td>
<td>3.3 mg/L</td>
</tr>
<tr>
<td>Design ww Flow Rate, Q</td>
<td>0.2 MGD</td>
</tr>
<tr>
<td>Influent NH₄-N Conc.</td>
<td>25 mg/L</td>
</tr>
<tr>
<td>Influent BOD, S₀</td>
<td>15 mg/L</td>
</tr>
<tr>
<td>Prim. Eff. Alkalinity</td>
<td>140 mg/L as CaCO₃</td>
</tr>
<tr>
<td>Min Design Temp., T</td>
<td>45°F</td>
</tr>
<tr>
<td>D.O Conc. in Reactor</td>
<td>3.0 mg/L</td>
</tr>
</tbody>
</table>

## 2. Preliminary Calculations - Design SALR value

<table>
<thead>
<tr>
<th>% NH₄-N removal</th>
<th>87%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum SARR</td>
<td>0.88 g/m²/d</td>
</tr>
<tr>
<td>NH₄-Nₑ @ SARRmax</td>
<td>0.80 mg/L</td>
</tr>
<tr>
<td>SARR @ NH₄-Nₑ, 15°C, SARR₁₅</td>
<td>0.88 g/m²/d</td>
</tr>
<tr>
<td>SARR @ NH₄-Nₑ, T°C, SARRₜ</td>
<td>0.57 g/m²/d</td>
</tr>
<tr>
<td>SARR Temp. Coeff., θ</td>
<td>1.058</td>
</tr>
<tr>
<td>Design Value for SALR</td>
<td>0.65 g/m²/d</td>
</tr>
</tbody>
</table>

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

### Inputs

- Carrier Spec. Surf. Area | 600 m²/m³
- Liquid Depth in Tank | 8 ft
- Tank L/W ratio | 1.6

### 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.

### Calculations

- NH₄-N Daily Loading | 41.7 lb/day |
- Calculated Tank Volume | 120.6 m³ |
- Tank Liquid Volume | 3576.2 m³ |
- BOD Surf. Loading Rate (SALR) | 0.39 g/m²/d |
- Design Average Flow | 193 min |
- Tank Liquid Volume | 3576.2 m³ |
- Nominal Hydraulic Retention Time at Design Average Flow | 193 min |
- Carrier Surf. Area needed | 28926 m² |
- Calculated Carrier Volume | 48.2 m³ |
- Calculated Tank Width | 18.8 ft |
- Calculated Tank Length | 28.2 ft |
- Carrier % Void Space | 60% |
- Liquid Depth in Tank | 8 ft |
- Tank L/W ratio | 1.6 |
- Tank Liquid Volume | 3576.2 m³ |
- Nominal Hydraulic Retention Time at Design Average Flow | 193 min |
- BOD Surf. Loading Rate (SALR) | 0.39 g/m²/d |
- Design Average Flow | 193 min |

---

**Screenshot of MBBR Process Design Calculations – Single Stage Nitrification – Part 1**
8. Two-Stage BOD Removal and Nitrification MBBR 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 in order to favor the nitrifying bacteria in the biomass attached to the carrier. 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 the figure below. As in the single stage nitrification process alkalinity is used for nitrification, so alkalinity addition is typically required.
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

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Treatment Target</th>
<th>Design SALR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Removal</td>
<td>g/m²-d</td>
</tr>
<tr>
<td>Nitrification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOD removal stage</td>
<td>90 - 95 (BOD₇)</td>
<td>6.0 (BOD₇)</td>
</tr>
<tr>
<td>Eff. NH₃-N &gt; 3 mg/L</td>
<td>90 (NH₃-N)</td>
<td>1.00 (NH₃-N)</td>
</tr>
<tr>
<td>Eff. NH₃-N &lt; 3 mg/L</td>
<td>90 (NH₃-N)</td>
<td>0.45 (NH₃-N)</td>
</tr>
</tbody>
</table>

The process design calculations for this two-stage MBBR process are essentially the same as those described above for the previous examples. Table 3 will be used to obtain values for SARR/SALR vs SALR for the BOD removal stage as in the previous examples. The design SALR for the nitrification stage will be calculated as it was for the single stage nitrification process.

The process design calculations for this two-stage process are illustrated in Example #6.

Example #6: A design wastewater flow of 1.5 MGD has the following primary effluent characteristics: 175 mg/L BOD, 35 mg/L TKN, and alkalinity of 140 mg/L as CaCO₃. The design minimum wastewater temperature is 45°F. This flow is to be treated for BOD removal and nitrification in a two stage MBBR process. The design SALR for the first stage is to be 6 g BOD/m²/d, the target effluent NH3-N from the second stage is to be 3.3 mg/L and the design DO level in the nitrification stage is to be 3.0 mg/L.

a) For the first (BOD removal) stage calculate each of the following:

i) The BOD loading
ii) The required carrier volume for a carrier with specific surface area of 600 m²/m³
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) For the second (Nitrification) stage calculate each of the following:

i) An appropriate NH₃-N surface area loading rate (SALR) to be used for this nitrification process, in g NH₃-N/m²/d.

ii) The nitrate loading

iii) The required carrier volume for a carrier with specific surface area of 600 m²/m³

iv) The required MBBR tank volume for a design carrier fill % of 40%

v) The volume of liquid in the MBBR reactor for design carrier void space of 60%.

vi) The average hydraulic retention time at design average wastewater flow and at design peak hourly flow if the design peak hour factor is 4.

vii) The alkalinity requirement in lb/day as CaCO₃ and in lb/day NaHCO₃.

Solution: The solution, as calculated with an Excel spreadsheet, is shown in the three spreadsheet screenshots on the next several pages. The first screenshot, which is the top part of the spreadsheet, shows primarily the user input values. It includes the calculation of the slope and intercept for the SARR/SALR vs SALR equation and the calculation of the estimated SARR for the BOD removal stage. It also includes calculation of the design SALR value for the nitrification stage. These calculations are carried out as discussed above for the single-stage BOD removal and nitrification MBBR processes. The resulting values for SARR/SALR are 0.935 for the first stage with SALR = 6 g BOD/m²/d, and 0.63 g/m²/d for the second stage (nitrification) SALR.

The second screenshot 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 (1.5 MGD)(175 mg/L)(8.34 lb/MG/mg/L) = 2,189 lb/day = (2189 lb/day)*(453.59 g/lb) = 993,022 g BOD/day

ii) Required carrier surface area = (993022 g/day)/(6 g/m²/day) = 165,504 m².

iii) Required carrier volume = 165,504 m²/600 m²/m³. = 275.8 m³

iv) For 40% carrier fill: Required tank volume = 275.8 m³/0.40 = 689.6 m³.

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

tank volume – [carrier volume( 1 – void %)]. Thus the volume of liquid is:

689.6 – [275.8(1 – 0.60)] = 579.3 m³ = 579.3(3.2808³) = 20,456 ft³.
v) The HRT at design average wastewater flow can be calculated as:
\[
HRT_{\text{ave}} = \frac{\text{reactor liquid volume} \times 7.48}{[Q \times 10^6/(24 \times 60)]}
\]
\[
= \frac{20,456 \times 7.48}{[1.5 \times 10^6/(24 \times 60)]} = \textbf{147 min}
\]

\[
HRT_{\text{peak hr}} = \frac{HRT_{\text{ave}}}{\text{peak hour factor}} = \frac{147}{4} = \textbf{37 min}
\]

### MBBR Process Design Calculations - U.S. units
Two-Stage Process for BOD Removal & Nitrification

**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 wastewater flow rate, Q | 1.5 MGD |
   | Peak Hour Factor | 4 |
   | Prim. Eff. Alkalinity | 140 mg/L as CaCO₃ |

2. **Parameters for First Stage**

   | Prim. Eff. BOD, $S_{\text{in}}$ | 175 mg/L |
   | Data points for SARR/SALR vs SALR |
   | Design Value of BOD Surface Loading Rate (SALR) | 6 g/m²/d |
   | Slope, SARR/SALR vs SALR | -0.007 |
   | Intercept, SARR/SALR vs SALR | 0.975 |
   | Est. of SARR/SALR Ratio | 0.975 |

3. **Parameters for Second Stage**

   | Influent NH₄-N Conc. | 35 mg/L |
   | Target Eff. NH₄-N Conc, $\text{NH}_4-N_{\text{e}}$ | 3.3 mg/L |
   | Min. Design Temp., $T$ | 45 °F |

4. **Preliminary Calculations - Design Nitrification SALR value**

   | % NH₄-N removal | 91% |
   | Maximum SARR | 0.88 g/m²/d |
   | $\text{NH}_4-N_{\text{e}}$ @ SARR = | 0.80 mg/L |
   | SARR @ $\text{NH}_4-N_{\text{e}}$, 15°C | 0.88 g/m²/d |
   | SARR @ $\text{NH}_4-N_{\text{e}}$, T °C | 0.57 g/m²/d |
   | SARR Temp. Coeff., $\Theta$ | 1.058 |
   | Design Value for nitrification SALR | 0.63 g/m²/d |

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

| Carrier Spec. Surf. Area | 600 m²/m³ |
| Carrier % Void Space | 60% |
| Tank L/W ratio | 1.5 (target L/W - only used if tank is rectangular) |

Screenshot of MBBR Process Design Calculations for Two Stage BOD Removal and Nitrification – Part 1
vi) Calculation of the estimated effluent BOD concentration from the first stage as shown above for the single stage BOD removal process gives a value of 11 mg/L.

b) For the second stage:

i) The design value for the nitrification SALR is 0.63 g/m²/d, calculated in the same way as it was for the single stage nitrification process.

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

#### 1. First Stage Calculations - BOD Removal

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Carrier Fill %</td>
<td>40% (for first stage)</td>
</tr>
<tr>
<td>BOD Daily Loading</td>
<td>2189.3 lb/day</td>
</tr>
<tr>
<td>Carrier Surf. Area needed</td>
<td>16500.7 ft²</td>
</tr>
<tr>
<td>Calculated Carrier Volume</td>
<td>2475.85 ft³</td>
</tr>
<tr>
<td>Tank Liquid Volume</td>
<td>2396.6 ft³</td>
</tr>
<tr>
<td>Calculated BOD Conc.</td>
<td>11 mg/L</td>
</tr>
</tbody>
</table>

#### 2. Second Stage Calculations - Nitrification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Carrier Fill %</td>
<td>40% (for second stage)</td>
</tr>
<tr>
<td>NH₃-N Daily Loading</td>
<td>437.9 lb/day</td>
</tr>
<tr>
<td>Carrier Surf. Area needed</td>
<td>316914 ft²</td>
</tr>
<tr>
<td>Calculated Carrier Volume</td>
<td>528.101 ft³</td>
</tr>
<tr>
<td>Tank Liquid Volume</td>
<td>42736 ft³</td>
</tr>
</tbody>
</table>

#### Estimate of BOD Surface Area and Nominal Hydraulic Retention Time at Removal Rate, SARR = 5.61 g/m²/d

Design Average Flow = 147 min
Est. of BOD Removal Rate: 928475 g/day
Calculated Eff. BOD Conc.: 11 mg/L

If the calculated Eff. BOD conc. is too high, the design value of the SALR should be reduced in cell C18.

To make the 2nd stage tank volume the same as the 1st stage, use Excel's Goal Seek process to set cell C71 equal to zero by changing the value in cell C58.

### Screenshot of MBBR Process Design Calculations for Two Stage BOD Removal and Nitrification – Part 2

ii) The NH₃-N loading rate will be \((1.5 \text{ MGD})(35 \text{ mg/L})(8.34 \text{ lb/MG/mg/L}) = 437.9 \text{ lb/day} = (437.9 \text{ lb/day}) \times (453.59 \text{ g/lb}) = 198,604 \text{ g NH₃-N/day}\)

iii) Required carrier surface area = \((198,604 \text{ g/day})/(0.63 \text{ g/m²/day}) = 316,914 \text{ m²}\).
Required carrier volume = 316914 m²/600 m²/m³ = 528.19 m³
= (528.19 m³)(3.28083 ft³/m³) = 18,652 ft³.

iv) For 40% carrier fill: Required tank volume = 18652 ft³/0.40 = 46,632 ft³.

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

    tank volume − [carrier volume( 1 − void %)], Thus the volume of liquid is:

    46632 − [18652(1 − 0.60)] = 42,736 ft³.

vii) The HRT at design ave ww flow can be calculated as:

    HRT_{des ave} = reactor liquid volume*7.48/[Q*10^6/(24*60)] = 42736*7.48/[1.5*10^6/(24*60)] = 307 min

HRT_{peak hr} = HRT_{des ave}/peak hour factor = 307/4 = 77 min

<table>
<thead>
<tr>
<th>V. Calculation of Alkalinity Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input: Target Effluent Alkalinity = 80 mg/L</td>
</tr>
<tr>
<td>Constants needed for Calculations:</td>
</tr>
<tr>
<td>Equiv Wt. of CaCO₃ = 50 g/equiv.</td>
</tr>
<tr>
<td>Equiv Wt. of NaHCO₃ = 84 g/equiv.</td>
</tr>
<tr>
<td>Alkalinity used for Nitrification = 7.14 g CaCO₃/g NH₃-N</td>
</tr>
<tr>
<td>Calculations</td>
</tr>
<tr>
<td>Alkalinity to be added = 166.3 mg/L as CaCO₃</td>
</tr>
<tr>
<td>Daily Alkalinity Requirement = 2080.9 lb/day as CaCO₃</td>
</tr>
<tr>
<td>For sodium bicarbonate use to add alkalinity:</td>
</tr>
<tr>
<td>Daily NaHCO₃ Requirement = 3495.9 lb/day NaHCO₃</td>
</tr>
</tbody>
</table>

Screenshot of MBBR Process Design Calculations for Two Stage BOD Removal and Nitrification – Part 3

vii) Calculation of the alkalinity requirement is shown in part 3 of spreadsheet screenshot, shown above. Using the equivalent weight of CaCO₃ as 50, the equivalent weight of NaHCO₃ as 84, the alkalinity use for nitrification as 7.14 g CaCO₃/g NH₃-N and the target effluent alkalinity as 80 mg/L as CaCO₃, give the calculated alkalinity requirement as 166.3 mg/L as CaCO₃. The rate of alkalinity addition needed can then be calculated as:
(1.5 MGD)(166.3 mg/L)*8.34 = \textbf{2080.9 lb/day as CaCO}_3. Multiplying this by the ratio of the equivalent weight of NaHCO\textsubscript{3} to the equivalent weight of CaCO\textsubscript{3} gives the daily NaHCO\textsubscript{3} requirement as \textbf{3495.9 lb/day NaHCO}_3.

9. Denitrification Background Information

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. Nitrification will only take place at a reasonable rate in an MBBR reactor 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 the figure below.

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 are described in the following two paragraphs.

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 anoxic denitrification reactor as shown in the flow diagram above.

In a post-anoxic denitrification process, the influent to the denitrification reactor comes from the nitrification reactor, so the wastewater influent ammonia nitrogen 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 for 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 (#5 and #6 at the end of the course) 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%


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 all three of these reactors the key design parameter for sizing the MBBR tank is the surface area loading rate (SALR), typically with units of g/m²/day, that is g/day (of the parameter being removed in that reactor) coming into the MBBR tank per m² of carrier surface area in the reactor.
Using design values for wastewater flow rate and concentration of the removed parameter entering the MBBR tank, the loading rate in g/day can be calculated. Then dividing the 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 post-anoxic denitrification MBBR process is shown in the figure on the next page.

![MBBR Flow Diagram for Post-Anoxic Denitrification](image)

Process design calculations for the BOD removal stage and the nitrification stage will be done just as described in Section 8, Two-Stage BOD Removal and Nitrification Process Design Calculations, and illustrated with the examples in that section. The process design calculations for denitrification, which is the third stage in a post-anoxic denitrification process, are similar to those previously discussed and illustrated for the BOD removal stage and the nitrification stage. The graph shown in the figure below (prepared using values from a similar graph in Rusten and Paulsrud’s presentation in Ref #4 at the end of this course) will be used to obtain values for SARR/SALR vs SALR for the denitrification stage.

![SARR vs SALR for Post-Anoxic Denitrification](image)
Table 4 below shows typical SALR design values for pre-anoxic denitrification and post-anoxic denitrification in MBBR reactors. Reference #2 at the end of this book is the source for the values in Table 4.

Table 4. Typical Design SALR Values for Denitrification

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Treatment Target</th>
<th>Design SALR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denitrification</td>
<td>(C/N &gt; 4)</td>
<td></td>
</tr>
<tr>
<td>Pre-DN</td>
<td>70 (NO₃-N)</td>
<td>0.90 (NO₃-N)</td>
</tr>
<tr>
<td>Post-DN</td>
<td>90 (NO₃-N)</td>
<td>2.00 (NO₃-N)</td>
</tr>
</tbody>
</table>

Example #7: A design wastewater flow of 1.5 MGD containing 175 mg/L BOD, 35 mg/L TKN, and alkalinity of 140 mg/L as CaCO₃ (in the primary effluent) is to be treated in a post-anoxic denitrification MBBR process. The design SALR for the first stage is to be 6 g BOD/m²/d. For the second stage, the SALR should be calculated for a target effluent NH₄-N conc. of 3.3 mg/L, min. design temperature of 45°F, and D.O. in reactor of 3.0 mg/L. For the post-anoxic stage, the SALR is to be 2 g NO₃-N/m²/d and the target effluent NO₃-N conc. is to be 5.0 mg/L.

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 600 m²/m³
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 NO₃-N concentration from the denitrification stage.
vii) The alkalinity requirement in lb/day as CaCO₃ and in lb/day NaHCO₃, for target effluent alkalinity of 80 mg/L as CaCO₃.
viii) The methanol requirement in lb/day for methanol use as the carbon source.

Note that the process design calculations for the BOD removal stage and the nitrification stage of this process will be the same as those used in Example #6 in the section on a two-stage BOD removal and nitrification process.
**Solution** - The solution is shown in the three figures on the next several pages, which are screenshots of different parts of an Excel worksheet used to carry out the calculations for this example. The first figure 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, resulting in a value of **SARR/SALR = 0.85**. The second figure is from the middle of the worksheet and shows the answers for parts i) through vi), as follows:

i) The NO$_3$-N loading rate will be $(1.5 \text{ MGD})(35 - 3.3 \text{ mg/L})(8.34 \text{ lb/MG/mg/L}) = 396.6 \text{ lb/day} = (396.6 \text{ lb/day})*(453.59 \text{ g/lb}) = 179,879 \text{ g NO}_3\text{-N/day}$

ii) Required carrier surface area = $(179,879 \text{ g/day})/(2 \text{ g/m}^2/\text{day}) = 89,939 \text{ m}^2$. Required carrier volume = $89,939 \text{ m}^2/600 \text{ m}^2/\text{m}^3 = 149.90 \text{ m}^3$

iii) For 40% carrier fill: Required tank volume = $149.90 \text{ m}^3/0.40 = 374.75 \text{ m}^3$.

iv) The volume of liquid in the reactor can be calculated as:
   tank volume – [carrier volume( 1 – void %)], Thus the volume of liquid is:
   $374.75 – [149.90(1 – 0.60)] = 314.79 \text{ m}^3 = 314.79*3.28083 = 11,117 \text{ ft}^3$.

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)]
   $= 11,117*7.48/[1.5*10^6/(24*60)] = 80 \text{ min}$

   HRT$_{peak\ hr}$ = HRT$_{des\ ave}$/peak hour factor = $80/4 = 20 \text{ min}$

vi) Calculation of the estimated effluent NO$_3$-N concentration from the second stage, as shown above for the BOD removal process, is shown in the Figure 35 spreadsheet screenshot below and gives a value of **4.8 mg/L**.

vii) Calculation of the alkalinity requirement is shown in the third 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, the alkalinity produced by denitrification as 3.56 g CaCO$_3$/g NO$_3$-N denitrified, 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:

   $(1.5 \text{ MGD})(81.9 \text{ mg/L})*8.34 = 1024.9 \text{ lb/day as CaCO}_3$. 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 **1721.8 lb/day NaHCO$_3$**.
viii) Calculation of the methanol requirement in lb/day is shown at the bottom of the third screenshot below. 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: \(\frac{4.6}{1.5} = 3.1\) 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 337.1 lb/day, or **1033.7 lb/day**.
# MBBR Process Design Calculations - U.S. units

## Post-Anoxic Denitrification Process

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

## 1. Wastewater Parameter Inputs

### 1. Parameters for All Three Stages

<table>
<thead>
<tr>
<th>Design wv Flow Rate, $Q_d$</th>
<th>Prim. Eff. BOD, $S_0$</th>
<th>Prim. Eff. NO$_3$-N Conc.</th>
<th>Prim. Eff. Alkalinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 MGD</td>
<td>175 mg/L</td>
<td>0 mg/L</td>
<td>140 mg/L as CaCO$_3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prim. Eff. TKN Conc.</th>
<th>Peak Hour Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 mg/L</td>
<td>4</td>
</tr>
</tbody>
</table>

## 2. Parameters for First (BOD Removal) Stage:

Data points for SARR/SALR vs SALR

<table>
<thead>
<tr>
<th>Design Value of BOD Surface</th>
<th>Data points for SARR/SALR vs SALR</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>15.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area Loading Rate (SALR)</th>
<th>SALR (g/m$^2$/d)</th>
<th>SARR/SALR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 g/m$^2$/d</td>
<td>0.925</td>
<td>0.875</td>
</tr>
</tbody>
</table>

See information on typical design values for SALR at right.

(default values above are from the table of typical values of % BOD removal vs SARR shown at the right from ref #2)

<table>
<thead>
<tr>
<th>Est. of SARR/SALR Rate</th>
<th>0.935</th>
</tr>
</thead>
</table>

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

Slope, SARR/SALR vs SALR: -0.007

Intercept, SARR/SALR vs SALR: 0.975

## 3. Parameters for Second (Nitrification) Stage:

<table>
<thead>
<tr>
<th>Influent NH$_4$-N Conc.</th>
<th>Target Eff. NH$_4$-N Conc, $NH_4-N_e$</th>
<th>Min Design Temp., $T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mg/L</td>
<td>3.3 mg/L</td>
<td>45°F</td>
</tr>
</tbody>
</table>

Click on cell B26 and on arrow to select D.O Conc.

<table>
<thead>
<tr>
<th>D.O Conc. in Reactor</th>
<th>3.0 mg/L</th>
</tr>
</thead>
</table>

## 4. Preliminary Calculations - Design Nitrification SALR value

<table>
<thead>
<tr>
<th>% NH$_4$-N removal</th>
<th>NH$_4$-N$<em>e$ @ SARR$</em>{max}$</th>
<th>Maximum SARR</th>
</tr>
</thead>
<tbody>
<tr>
<td>87%</td>
<td>3.3 mg/L</td>
<td>0.80 g/m$^2$/d</td>
</tr>
</tbody>
</table>

SARR @ NH$_4$-N$_e$, 15°C, SARR$_{15}$ = 0.88 g/m$^2$/d

SARR @ NH$_4$-N$_e$, T°C, SARR$_T$ = 0.67 g/m$^2$/d

SARR Temp. Coeff, $\theta$ = 1.058

Design Value for nitrification SALR = 0.65 g/m$^2$/d

## 5. Parameters for Third (Post-Anoxic) Stage:

Data points for SARR/SALR vs SALR

<table>
<thead>
<tr>
<th>Target Eff. NO$_3$-N Conc.</th>
<th>Design Value of BOD Surface</th>
<th>SARR/SALR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0 mg/L</td>
<td>0.880 g/m$^2$/d</td>
<td>0.850</td>
</tr>
</tbody>
</table>

Area Loading Rate (SALR) = 2.0 g/m$^2$/d

See information on typical design values for SALR at right.

(default values above are from a graph of Post-Anoxic SARR vs SALR in ref #6 below right)

(The graph is shown at the right.)

<table>
<thead>
<tr>
<th>Est. of SARR/SALR Rate</th>
<th>Slope, SARR/SALR vs SALR</th>
<th>Intercept, SARR/SALR vs SALR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85</td>
<td>-0.030</td>
<td>0.910</td>
</tr>
</tbody>
</table>

(Surf. Area Removal Rate/Surf. Area Loading Rate)
### II. Determine whether to use Pre-Anoxic or Post-Anoxic Denitrification

Carbon Nitrogen Ratio, $C/N = 5.0$

Target $\%$ N removal = 86%

Use this Worksheet for Post-Anoxic Denitrification calculations

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

- Carrier Spec. Surf. Area = 600 $m^2/m^3$
- Liquid Depth in Tank = 8 ft
- Tank L/W ratio = 1.5

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)

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

#### 3. Third Stage (Post-Anoxic) Calculations

- Design Carrier Fill % = 32% (for third stage)
- $NO_3-N$ Daily Loading = 396.6 lb/day
- $NO_3-N$ Daily Loading = 178879 g/day
- Carrier Surf. Area needed = 69939 $m^2$
- Calculated Carrier Volume = 149.90 $m^3$
- Tank Liquid Volume = 14581.6 $ft^3$

Required Tank Volume = 472.06 $m^3$

Tank Liquid Volume = 16699.0 $ft^3$

Calculated Tank Width = 37.3 ft

Calculated Tank Length = 56.0 ft

Nominal Hydraulic Retention Time at Design Average Flow = 105 min

Peak Hourly Flow = 26 min

$Est. \ of \ NO_3-N \ Removal \ Rate$ = 152897 g/day

$Est. \ of \ NO_3-N \ Removal \ Rate$ = 337.1 lb/day

$Calculated \ Eff. \ NO_3-N \ Conc.$ = 4.8 mg/L

If the calculated Eff. NO$_3-N$ conc. is too high, the design value of SALR (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.
### 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 the figure below (prepared using values from a similar graph in Rusten and Paulsrud’s presentation in Ref #4 at the end of this course) will be used to obtain values for SARR/SALR vs SALR for the pre-anoxic denitrification stage.
A typical flow diagram for a pre-anoxic denitrification MBBR process is shown in the figure 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.

Process Design calculations 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 is used as the carbon source for the denitrification reactions in the pre-anoxic tank. For the pre-anoxic process, the BOD loading rate (in lb/day) should be calculated as:

\[
\text{BOD Daily Loading} = (Q_o \cdot S_o \cdot 8.34) - (0.67 \cdot (20/7) \cdot \text{NO}_3-N \text{ removal rate})
\]

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 Example #7. [1.5 MGD containing 175 mg/L BOD and 35 mg/L TKN (in the primary effluent)]. Consider that the primary effluent alkalinity is 140 mg/L as CaCO₃ and the design SALR for the denitrification stage is to be 0.9 g NO₃-N/m²/d. The nitrification stage was designed for an effluent NH₃-N concentration of 3.3 mg/L, a D.O. of 3.0 mg/L, and a minimum WW temperature of 45°F.

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

i) The nitrate loading rate
ii) The required carrier volume for a carrier with specific surface area of 600 m²/m³
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 NO₃-N recycle rate needed to achieve a target effluent NO₃-N concentration of 9 mg/L.
vii) The alkalinity requirement in lb/day as CaCO₃ and in lb/day NaHCO₃, for a target effluent alkalinity of 80 mg/L as CaCO₃.

Solution - The solution is shown in the three figures on the next several pages, which are screenshots of different parts of an Excel worksheet used to carry out the calculations for this example. The first figure below 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 (calculated to be 0.927). Note also that a user input value is needed for the estimated NO₃-N recycle ratio. This initial estimated value is used in an iterative calculation farther down on the worksheet (in the second screenshot below) to determine
the required NO₃-N recycle ratio needed to achieve the target effluent NO₃-N concentration.

The figure, on the next page, 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 NO₃-N recycle flow rather than in the primary effluent flow entering the tank. The NO₃-N loading rate will be:

\[(1.5 \text{ MGD})(\text{Prim Effl NO}_3-N)(8.34 \text{ lb/MG/mg/L}) + (1.5 \text{ MGD})(\text{Recycle Ratio})(\text{Target Effl NO}_3-N)(8.34) = 306.5 \text{ lb/day} \]

\[= (306.5 \text{ lb/day})*(453.59 \text{ g/lb}) = \text{139,003 g NO}_3-N/\text{day} \]

ii) Required carrier surface area = (139,003 g/day)/(0.9 g/m²/day) = 154,447 m².

Required carrier volume = 154,447 m²/600 m²/m³ = 257.41 m³ = (257.41 m³)(3.28083 ft³/m³) = 9090 ft³.

iii) For 40% carrier fill: Required tank volume = 9090 ft³/0.40 = 22,726 ft³ (643.5 m³)
iv) The volume of liquid in the reactor can be calculated as:
\[
\text{tank volume} - \text{[carrier volume( 1 – void %)]}. \text{Thus, the volume of liquid is:}
\]
\[
22,726 - [9090(1 - 0.60)] = 19,090 \text{ ft}^3 \quad (540.6 \text{ m}^3)
\]

vi) The HRT at design ave WW flow can be calculated as:
\[
\text{HRT}_{\text{des ave}} = \frac{\text{reactor liquid volume} \times 7.48}{\text{Q} \times 10^6/(24 \times 60)}
\]
\[
= 19,090 \times 7.48/[1.5 \times 10^6/(24 \times 60)] = 137 \text{ min}
\]
HRT_{peak \ hr} = \frac{HRT_{des \ ave}}{\text{peak hour factor}} = \frac{137}{4} = \textbf{34 min}

vii) The required NO₃-N recycle ratio is calculated with the iterative process described in blue at the bottom of the last figure above. For this iterative process, the NO₃-N removal rate is calculated two different ways, one using the estimated SARR and the carrier surface area while the other uses the wastewater flow rate times the influent TKN concentration minus the sum of the effluent nitrate and ammonia nitrogen concentrations. 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 NO₃-N recycle ratio. This process results in the required NO₃-N recycle ratio calculated to be 2.72.

viii) Calculation of the alkalinity requirement is shown in the third screenshot figure, below on this page. Using the equivalent weight of CaCO₃ as 50, the equivalent weight of NaHCO₃ as 84, the alkalinity use for nitrification as 7.14 g CaCO₃/g NH₃-N, the alkalinity produced by denitrification as 3.56 g CaCO₃/g NO₃-H, and the target effluent alkalinity as 80 mg/L as CaCO₃, give the calculated alkalinity requirement as 97.1 mg/L as CaCO₃. The rate of alkalinity addition needed can then be calculated as:

\( (1.5 \text{ MGD})(91.1 \text{ mg/L}) \times 8.34 = \textbf{1214.5 lb/day as CaCO₃} \). Multiplying this by the ratio of the equivalent weight of NaHCO₃ to the equivalent weight of CaCO₃ gives the daily NaHCO₃ requirement as \textbf{2040.3 lb/day NaHCO₃}.

### VII. Calculation of Alkalinity Requirements

<table>
<thead>
<tr>
<th>Input:</th>
<th>Target Effluent Alkalinity = 80 mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constants needed for Calculations:</td>
<td></td>
</tr>
<tr>
<td>Equiv Wt. of CaCO₃ = 50 g/equiv.</td>
<td>Equiv Wt. of NaHCO₃ = 84 g/equiv.</td>
</tr>
<tr>
<td>Alkalinity used for Nitrification = 7.14 g CaCO₃/g NH₃-N removed</td>
<td>Alkalinity produced by Denitrification = 3.57 g CaCO₃/g NO₃-H removed</td>
</tr>
<tr>
<td>Calculations</td>
<td></td>
</tr>
<tr>
<td>Alkalinity to be added = 97.1 mg/L as CaCO₃</td>
<td>Daily Alkalinity Requirement = 1214.5 lb/day as CaCO₃</td>
</tr>
<tr>
<td>Daily NaHCO₃ Requirement = 2040.3 lb/day NaHCO₃</td>
<td>For sodium bicarbonate use to add alkalinity:</td>
</tr>
</tbody>
</table>
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 carriers. The required reactor size for an MBBR process is typically significantly smaller than that 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 two-stage BOD removal MBBR system, a single stage tertiary nitrification MBBR system, a two-stage BOD removal/Nitrification MBBR system a post-anoxic denitrification MBBR system and a pre-anoxic denitrification MBBR system.

13. References


