Biological Wastewater Treatment Processes III: *MBR Processes*

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Credit: 2 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. The second 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. This course (Part III) of this series is about the Membrane Bioreactor (MBR) 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 MBR process and numerous example calculations.

2.   Learning Objectives

At the conclusion of this course, the student will

- Be familiar with the components of and general configuration of an MBR wastewater treatment process

- Know the advantages and disadvantages of an MBR wastewater treatment process in comparison with a conventional activated sludge process

- Know the type of pretreatment typically required for an MBR wastewater treatment process

- Be able to carry out process design calculations to determine the required membrane area, membrane module volume and scouring air flow rate

- Be able to carry out process design calculations for a BOD removal/nitrification MBR process in order to determine the required aeration tank volume, sludge wasting rate, air flow rate, and alkalinity addition

- Be able to carry out process design calculations for a Pre-Anoxic Denitrification MBR process in order to determine the required pre-anoxic tank volume, the reduced oxygen/air requirement, the reduced alkalinity requirement, the anoxic tank mixing power needed, and the sludge wasting rate

3.   Topics Covered in this Course

I. Description of the MBR (Membrane Bioreactor) Process

II. Membrane Module Process Design Calculations

III. Process Design Calculations for BOD Removal and Nitrification

IV. Process Design Calculations for Pre-Anoxic Denitrification

4.   Description of the MBR (Membrane Bioreactor) Process

Initial Development of the MBR Process: Membrane filtration has been used for quite some time in a variety of ways in water and wastewater treatment. It was not until the 1970's, however, that research at Rensselaer Polytechnic Institute proposed coupling the activated sludge process with membrane filtration. Dorr-Oliver introduced the first membrane bioreactor (MBR) wastewater treatment processes with a flat sheet ultrafiltration plate and frame membrane. This process was put into use in Japan in the 1970s and 1980s, but did not come into very widespread use around the world. In 1989 Yamamoto et al (Ref #2 at the end of this course) developed and introduced submerged membranes with a membrane module placed directly in the aeration tank rather than as a separate process following the aeration tank. This innovation accelerated interest in, development of, and spreading use of MBR wastewater treatment processes. Currently almost all MBR processes being installed have a submerged membrane module in the aeration tank, as shown in **Figure 1** below.
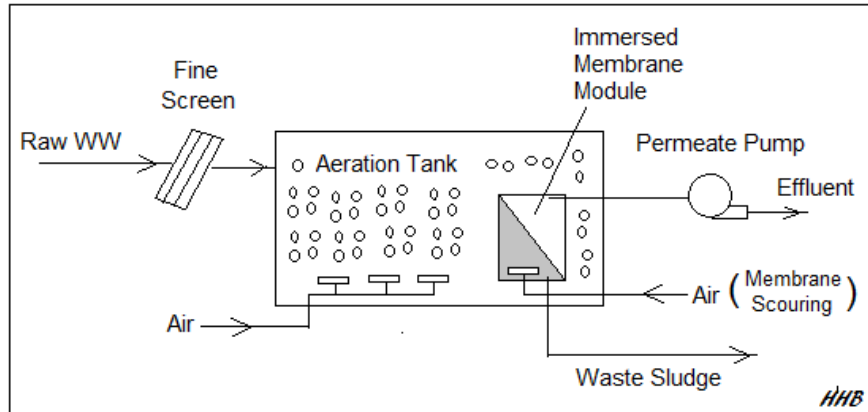
Figure 1. MBR Wastewater Treatment Typical Process Flow Diagram

Comparison of the MBR Process with Conventional Activated Sludge: The first difference to note is that the use of membrane filtration allows an MBR process to produce a significantly higher quality effluent than that obtainable from a conventional activated sludge process. Secondly, the mixed liquor suspended solids concentration (MLSS) and the solids retention time (SRT) are limited in a conventional activated sludge process by the need to produce a sludge with good settling characteristics in the secondary clarifier. This is not a requirement for MBR processes, because the final effluent is produced by filtration rather than by sedimentation. Thus, the MLSS and SRT can both be larger for MBR processes than the typical values used for conventional activated sludge. This results in a smaller aeration tank volume needed for an MBR process than that needed for conventional activated sludge treating the same wastewater flow.

On the other hand, the need to keep the membranes from getting fouled increases operating costs over typical values for conventional activated sludge. The method that has evolved for cleaning the membranes and keeping them from getting fouled is a fairly high rate of aeration below the membrane module, so that the air bubbles keep the membrane clean. This results in a higher aeration cost than that typically required for conventional activated sludge.

Pretreatment Prior to the MBR Aeration Tank: Primary clarification is not typically used before the MBR aeration tank, however, coarse screening and grit removal should be used if warranted by the wastewater characteristics, and fine screening (2 – 3 mm pore size) should be used as the final pretreatment step before the aeration tank.

MBR Wastewater Treatment Process Alternatives: The MBR wastewater treatment process alternatives that will be discussed in this course are the following:

1. BOD removal and Nitrification

2. BOD removal and Nitrification together with Pre-anoxic Denitrification

Overview of MBR Process Design Calculations: The membrane surface area requirement, volume requirement, and required scouring air flow rate for the membrane module can be calculated using membrane module properties typically available from membrane module manufacturers or vendors together with incoming wastewater information.

Sizing of the aeration tank will be done in a manner similar to that used for a completely mixed activated sludge process.

5. Membrane Module Process Design Calculations

The membrane module properties typically required for process design and their units are: 1) Average Membrane Flux, **J**, in $L/hr/m^2$, 2) Module Packing Density, ϕ, in m^2/m^3, and 3) Specific Aeration Demand, **SAD$_M$** in m^3 air/hr/m^2 membrane area. Using these membrane/membrane module properties, the required membrane area, membrane module volume, and scouring air flow rate can be calculated as follows:

Membrane area, **A$_M$ = Q$_o$/J**, where **Q$_o$** is the wastewater flow rate in L/hr. With **Q$_o$** in m^3/day, the equation with conversion factors becomes:

   A$_m$ = (Q$_o$/24)*1000/J.

With **Q$_o$** in MGD, the equation with conversion factors becomes:

   A$_m$ = (Q$_o$/24)*1000000/[(J/3.7854)/(3.2808^2)].

Note that in this case, the flow rate has been converted to gal/day and **J** has been converted to gal/hr/ft^2. The membrane module volume is then calculated as: **V$_M$ = A$_M$/ϕ**. For S.I. units no conversion factors are needed. For U.S. units, ϕ must be converted from m^2/m^3 to ft^2/ft^3.

The scouring air flow required to keep the membrane from getting fouled is calculated as: Required Scouring Air Flow = **SAD$_M$*A$_M$/60** . This gives the required scouring air flow in m^3/min. To calculate the required scouring air flow in cfm, SADM should be converted to ft^3 air/hr/ft^2 membrane.

Example #1: a) A design wastewater flow 7571 m^3/d is to be treated with an MBR wastewater treatment system. The design membrane module properties are: average membrane flux, **J** = 12 $L/hr/m^2$; module packing density, ϕ = 120 m^2/m^3; specific aeration demand, **SAD$_M$** = 0.3 m^3 air/hr/m^2 membrane. Calculate the required membrane area,

membrane module volume, and scouring air flowrate.b) Repeat for a design wastewater flow of 2 MGD with the same membrane module properties.

Solution: a) **Figure 2** below is a screenshot of an Excel spreadsheet set up to make the membrane module calculations described above for part a), with S.I. units. The given membrane module properties were entered in the blue cells. A_m, V_m and scouring air flow are calculated by the worksheet in the yellow cells, using the equations given above. Note that the specified wastewater flow rate of 7571 m^3/d is used in the calculations. As shown in Figure 2, the results are: A_m = 26,288 m^2, V_m = 219 m^3, and scouring air flow required = 131 m^3/min.

b) The **Figure 3** below is a similar screenshot with the calculations in U.S. units, as described above. In this worksheet the specified wastewater flow rate of 2 MGD is used in the calculations. The results in U.S. units are: A_m = 282,956 ft^2, V_m = 7736 ft^3, and scouring air flow required = 4642 cfm.

MBR Process Design Calculations - S.I. units				
Membrane Module Sizing Calculations				

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

1. User Inputs, Membrane/Membrane Module Parameters:
(values typically available from membrane manufacturer or vendor)

Ave. Membrane Flux, J =	12	L/hr/m^2	Spec. Aer. Demand, SAD_M =	0.3
Module packing			(m^3 air/hr/m^2 membrane)	
density, ϕ =	120	m^2/m^3		

2. Process Design Calculations (done by worksheet)

Membrane Area, A_M =	26,288	m^2	Membrane Module Vol., V_M =	219	m^3
Scouring Air Flow Required:	131	m^3/min (ACMM) =	135	SCMM	

(This is the scouring air flow rate needed for the membrane module, typically provided by a coarse bubble diffuser system.)

Figure 2. Excel Worksheet with Membrane Module Calculations – S.I. units

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MBR Process Design Calculations - U.S. units
   Membrane Module Sizing Calculations

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

1. User Inputs,  Membrane/Membrane Module Parameters:
            (values typically available from membrane manufacturer or vendor)

Ave. Membrane Flux, J =    [ 12 ]   L/hr/m²  =   [ 0.295 ]   gal/hr/ft²
Module packing
        density, φ =       [ 120 ]   m²/m³  =   [ 36.6 ]    ft²/ft³
Spec. Aer. Demand,  SAD_M =  [ 0.3 ]  m³ air/hr/m² membrane  =   [ 0.984 ]
                                                     (ft³ air/hr/ft² membrane)
2. Process Design Calculations  (done by worksheet)

Membrane Area, A_M =  [ 282,956 ]  ft²    Membrane Module Vol., V_M =  [ 7,736 ]  ft³


Scouring Air Flow Required:  [ 4642 ]  ft³/min   (ACFM)   =   [ 4768 ]   SCFM

(This is the scouring air flow rate needed for the membrane module,
       typically provided by a coarse bubble diffuser system.)
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Figure 3. Excel Worksheet with Membrane Module Calculations – U.S. units

6.   Process Design Calculations for BOD Removal and Nitrification

The aeration tank will be essentially a completely mixed tank, so the process design calculations for the aeration tank can be done using a completely mixed activated sludge (CMAS) process design procedure. The calculations described in this section and illustrated with example calculations follow the CMAS process design procedure presented in Metcalf & Eddy's 4th edition of *Wastewater Engineering, Treatment and Reuse*, which is the first reference in the list at the end of this book.

Required User Inputs: Quite a few user inputs are needed for the Metcalf & Eddy CMAS process design procedure. The **Figure 4** below, is an Excel spreadsheet screenshot showing the wastewater parameters/characteristics inputs needed for the MBR process design calculations. The **Figure 5** below is another screenshot showing the biological kinetic coefficients for BOD removal and for nitrification that are needed, along with a couple of constants. The values shown in these two figures will be used in the example calculations in this course.

MBR Process Design Calculations - U.S. units
User Inputs and Constants

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

User Inputs - Wastewater Parameters/Characteristics

Design ww Flow Rate, Q_o =	2	MGD	Influent TSS, TSS_o =	160	mg/L
Influent BOD, BOD_o =	210	mg/L	Influent VSS, VSS_o =	128	mg/L
sBOD, $sBOD_o$ =	120	mg/L			
			Influent TKN, TKN_o =	37	mg/L
Influent COD, COD_o =	419	mg/L	TKN peak/ave factor , FS =	1.5	
sCOD, $sCOD_o$ =	200	mg/L	Influent NH_4-N, NH_4-N_o =	25.9	mg/L
rbCOD, $rbCOD_o$ =	100	mg/L	Influent Alkalinity, Alk_o =	140	mg/L as $CaCO_3$
ratio, $bCOD/BOD$ =	1.6		Aeration WW Temp., T_{ww} =	54	°F

Figure 4. Wastewater Parameter/Characteristics Inputs – U.S. units

User Inputs - Biological Kinetic Coefficients   (See typical values at right)

1. For BOD Removal:			Resid. biomass fract., f_d =	0.15	
Synth. Yield Coeff, Y =	0.4	lb VSS/lb bCOD	Half Veloc. Coeff., K_s =	20	mg/L
Temp coeff, θ, for μ_m =	1.07		Max spec. grwth rate at 20°C, μ_{m20} =	6	lb VSS/d/lb VSS
Temp coeff, θ, for k_d =	1.04		Endog. decay coeff. at 20°C, k_{d20} =	0.12	lb VSS/d/lb VSS
2. For Nitrification:					
Synth. Yield Coeff, Y_n =	0.12	lb VSS/lb NOx			
Temp coeff, θ, for μ_{mn} =	1.07		Max spec. grwth rate at 20°C, μ_{mn20} =	0.45	lb VSS/d/lb VSS
Temp coeff, θ, for k_{dn} =	1.04		Endog. decay coeff. at 20°C, k_{dn20} =	0.08	lb VSS/d/lbVSS
Temp coeff, θ, for K_{sn} =	1.053		Half Veloc. Coeff. At 20°C, K_{sn} =	0.4	mg/L

Constants Used in the Calculations

Ratio of BOD_5 to BOD_u, f =	0.67		BOD_u equiv. of VSS =	1.4	lb BOD_u/lb VSS

Figure 5. Inputs for Biological Kinetic Coefficients and Constants – U.S. units

Table 1, on the next page, shows ranges and typical values for the BOD removal biological kinetic coefficients. **Table 2** provides similar information for nitrification removal and biological kinetic constants.

Activated Sludge Kinetic Coefficients for heterotrophic bacteria at 20°C (for BOD removal

Coefficient	Unit	Range	Typical Value
μ_m	kg VSS/day/kg VSS	3.0 - 13.2	6.0
K_s	mg/L bCOD	5.0 - 40.0	20.0
Y	kg VSS/day/kg bCOD	0.30 - 0.50	0.40
k_d	kg VSS/day/kg VSS	0.06 - 0.20	0.12
f_d	dimensionless	0.08 - 0.20	0.15

θ values for temperature corrections

for μ_m	dimensionless	1.03 - 1.08	1.07
for k_d	dimensionless	1.03 - 1.08	1.04
for K_s	dimensionless	1.00	1.00

Adapted from: Metcalf & Eddy, Inc, (Revised by Tchobanoglous, G, Burton, F.L., Stensel, H.D., *Wastewater Engineering, Treatment and Reuse,* 4th Ed., New York, NY, 2003.

Table 1. Ranges and Typical Values for Biological Kinetic Coefficients – BOD Removal

Activated Sludge Nitrification Kinetic Coefficients at 20°C			
Coefficient	Unit	Range	Typical Value
μ_{mn}	kg VSS/day/kg VSS	0.2 - 0.90	0.75
K_n	mg/L NH_4-N	0.50 - 1.0	0.74
Y_n	kg VSS/kg NH_4-N	0.10 - 0.15	0.12
k_{dn}	kg VSS/day/kg VSS	0.05 - 0.15	0.08
K_o	mg/L	0.40 - 0.60	0.50
θ values for temperature corrections			
for μ_{mn}	dimensionless	1.06 - 1.123	1.07
for k_{dn}	dimensionless	1.03 - 1.08	1.04
for K_n	dimensionless	1.03 - 1.123	1.053
Adapted from: Metcalf & Eddy, Inc, (Revised by Tchobanoglous, G, Burton, F.L., Stensel, H.D., *Wastewater Engineering, Treatment and Reuse*, 4th Ed., New York, NY, 2003.			

Table 2. Ranges and Typical Values for Biological Kinetic Coefficients – Nitrification

Some additional user inputs are needed for the BOD removal/nitrification process design calculations, as shown in **Figure 6**, the first Excel spreadsheet screenshot shown below. The next Excel spreadsheet screenshot, **Figure 7**, shows the results of the first two steps of the process design calculations made by the spreadsheet based on the user inputs shown previously. Those first two steps are calculation of the design SRT and calculation of the biomass production rate. The equations used for those calculations are as shown below the two screenshots. These calculations are the same for either U.S. units or S.I. units.

MBR Process Design Calculations - U.S. units
BOD Removal and Nitrification

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

User Inputs:
Target effluent concentrations:

$BOD_e =$	10	mg/L	MLSS in Aer. Tank, $X_O =$	10,000	mg/L
$TSS_e =$	10	mg/L	MLSS in Waste Sludge, $X_W =$	14,000	mg/L
$NH_4\text{-}N_e =$	1	mg/L	Tank Freeboard $=$	1.5	ft
DO in Aer. Tank, $DO_O =$	1.5	mg/L	Number of Aeration Tanks $=$	3	
Influent TKN, $TKN_o =$	37	mg/L	Liquid Depth in Tank $=$	15	ft
(value transferred from Worksheet 2)			Tank L:W ratio $=$	1.0	
Initial Estimate of NOx $=$	27.6	mg/L	(target L:W - only used if tank is rectangular)		

NOTE: An initial estimate is needed for NOx in cell C14 to start an iterative calculation of NOx below. 80% of the influent TKN is suggested for this initial estimate.

Figure 6. User Inputs for MBR Process Design Calculations – BOD Removal and Nitrification

Process Design Calculations (done by worksheet)

1. Calculate Design SRT

μ_{mn} at $T_{ww} =$	0.27	lb VSS/d/lb VSS	K_{sn} at $T_{ww} =$	0.27	mg/L
k_{dn} at $T_{ww} =$	0.06	lb VSS/d/lb VSS	$\mu_n =$	0.10	lb VSS/d/lb VSS
Theoretical SRT $=$	10.2	days	Design SRT, $SRT =$	15.3	days

2. Calculate the Biomass Production Rate

μ_m at $T_{ww} =$	3.5	lb VSS/d/lb VSS	k_d at $T_{ww} =$	0.088	lb VSS/d/lb VSS
$bCOD_o =$	336	mg/L	$S =$	0.91	mg bCOD/L

Biomass Production Rate, $P_{X,bio} =$	1173	lb VSS/day

Figure 7. Calculation of Design SRT and Biomass Production Rate

Equations for calculation of Design SRT:

$$\mu_{nm} \text{ at } T_{ww} = \mu_{nm,20}\, \theta^{T_{ww}-20} \qquad K_n \text{ at } T_{ww} = K_{n,20}\, \theta^{T_{ww}-20}$$

$$k_{dn} \text{ at } T_{ww} = k_{dn,20}\, \theta^{T_{ww}-20} \qquad \text{(Tww must be in } ^{o}\text{C for these calculations)}$$

$$\mu_n = [\, \mu_n N/(K_n + N)\,][\, DO/(K_o + DO)\,] - k_{dn} \qquad \textbf{Theoretical SRT} = 1/\mu_n$$

$$\textbf{Design SRT} = \textbf{(FS)(Theoretical SRT)} \qquad FS = TKN_{peak}/TKN_{average}$$

Equations for calculation of Biomass Production Rate:

$$\mu_m \text{ at } T_{ww} = \mu_{m,20}\, \theta^{T_{ww}-20} \qquad k_d \text{ at } T_{ww} = k_{d,20}\, \theta^{T_{ww}-20}$$

$$S = K_s[1 + (k_d)SRT]/[SRT(\mu_m - k_d) - 1]$$

$$P_{X,bio} = QY(S_o - S)(8.34)/(1 + k_d SRT) + f_d k_d QY(S_o - S)(8.34)SRT/(1 + k_d SRT) +$$

$$QY_n(NO_x)(8.34)/(1 + k_{dn}SRT)$$

Note that the equation for $P_{X,bio}$, as shown above, is for use with U.S. units (Q in MGD). For S.I. units with Q in m^3/d, the 8.34 conversion factor [(lb/MG}/(mg/L)] should be replaced with (1/1000) to convert g/day to kg/day.

Figure 8 below shows the calculation of the amount of nitrogen oxidized to nitrate (NO_x), using the following equation: $NO_x = TKN - N_e - 0.12P_{X,bio}/Q$

The iterative procedure described in blue sets the difference between the estimated and calculated values of NOx to zero by changing the initial estimated value in cell C14 (shown in **Figure 6**). These calculations are the same for either U.S. or S.I. units

3. Determine the Amount of Nitrogen Oxidized to Nitrate				
Calculated amount of nitrogen oxidized to nitrate, **NOx** =		27.6	mg/L	
Difference between estimated and calculated values for **NOx** =		0.000	mg/L	
Goal Seek Result:				
Amount of nitrogen oxidized to nitrate, **NOx** =		**27.6**	mg/L	

NOTE: This is an iterative solution. You must use Excel's "Goal Seek" to find the NOx value as follows: Place the cursor on cell G36 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:" G36, "To value:" 0, "By changing cell:" C14, and click on "OK". The calculated value of NOx will appear in cell E38 and cell G36 should be zero if the process worked properly. Note that cell C14 needs an initial estimate for NOx in order for the iterative solution to work properly.

Figure 8. Calculation of Amount of Nitrogen Oxidized to Nitrate

Figure 9 shows the calculation of the production rate and mass of VSS and TSS in the aeration tank, using the following equations:

bpCOD/pCOD = (BODo - sBODo)/(CODo - sCODo)

nbVSS = [1 - (bpCOD/pCOD)VSSo]

$P_{X,VSS}$ = $P_{X,bio}$ + Q(nbVSS*8.34)

$P_{X,TSS}$ = $P_{X,bio}$/(VSSo/TSSo) + Q(nbVSS*8.34) + Q(TSS$_o$ - VSS$_o$)8.34

Note that the equations for $P_{X,VSS}$ and $P_{X,TSS}$, as shown above, are for use with U.S. units (Q in MGD). For S.I. units with Q in m^3/d, the 8.34 conversion factor [(lb/MG}/(mg/L)] should be replaced with (1/1000) to convert g/day to kg/day.

Mass of MLVSS = ($P_{X,VSS}$) SRT   **Mass of MLSS = ($P_{X,TSS}$) SRT**

4. Determine the Production Rate and Mass of VSS and TSS in the Aeration Basin					
bpCOD/pCOD =	0.658		**nbVSS =**	43.8	
Aeration Tank VSS Production Rate, $P_{X,VSS}$ =			1904	lb VSS/day	
Aeration Tank TSS Production Rate, $P_{X,TSS}$ =			2732	lb TSS/day	
			21163		
Mass of **MLVSS** =	29,052	lb VSS	Mass of **MLSS** =	41,669	lb TSS

Figure 9. Calculation of Production Rate and Mass of VSS and TSS in Aeration Tank

Figure 10 shows the calculation of the aeration tank volume and dimensions, the detention time and the MLVSS concentration, using the following equations:

V = [Mass of MLSS/(MLSS*8.34)]*(1,000,000/7.48)   (for V in ft³ and Mass of MLSS in lb)

V = Mass of MLSS*1000/MLSS   (for V in m³ and Mass of MLSS in kg)

Detention time: $\tau = V/Q$ - The actual equation used to calculate the detention time in U.S. units with **V** in ft³ and **Q** in MGD is: **$\tau = [(V*7.48/1,000,000)*(N*24)]/Q$,** where **V** is the actual aeration tank volume for each tank and **N** is the number of aeration tanks.

For S.I. units with V in m³ and Q in m³/d, the equation is: **$\tau = [V*(N*24)]/Q$**

MLVSS = MLSS*(Mass of MLVSS/Mass of MLSS)

Also, the equation for the volume of a rectangular tank or the volume of a cylindrical tank is used (along with the user specified depth of water in the tank (and the L:W ratio if it is rectangular) to calculate the length and width or diameter of the aeration tank.

5. Calculate Aeration Tank Volume and dimensions, Detention Time, and MLVSS					
(User Input needed in Blue Cells)					
Req. Aeration Vol., V_{aer} =	66,796	ft³	Click on green box and then on		
Aer. + Membr. Vol., V_{tot} =	74,532	ft³	arrow to Select Tank Shape:	**rectangular**	
Req. Vol. per tank, V_{tank} =	24,844	ft³	**Actual Tank Width:**	41.0	ft
Calculated Tank Width =	40.7	ft	**Actual Tank Length:**	41.0	ft
Calculated Tank Length =	40.7	ft	Actual Tank Aeration Volume =	22636	ft³
Tank Wall Height =	16.5	ft	Membrane Module Vol. per Tank =	2579	ft³
Aeration Det'n time, τ =	6.10	hr	**MLVSS, =**	6972	mg/L

Figure 10. Calc. of Aeration Tank Volume and Dimensions, Detention Time, & MLVSS

Figure 11 shows the calculation of the F/M ratio, the Volumetric BOD loading, and the sludge wasting rate, using the following equations:

F/M = QS₀/(V*MLVSS)

This equation can be used as it is for S.I. units with Q in m^3/day and V (the total volume of all aeration tanks) in m^3. For U.S. units with Q in MGD and V in ft^3, some conversion factors are needed, giving the following equation:

F/M = $QS_o/[(V*7.48/1,000,000)*MLVSS]$

For S.I. units with Q in m^3/d and V in m^3, the equation for volumetric BOD loading is:

Vol BOD loading = $QS_o(1/1000)/V$ NOTE: V is the total vol. of all aeration tanks.

For U.S. units with Q in MGD and V = total aeration vol. in ft^3, the volumetric BOD loading in lb BOD/d/1000 ft^3 can be calculated with the following equation:

Vol BOD loading = $QS_o*8.34/(V/1000)$

For S.I. units with total aeration tank volume, **V**, in m^3 the sludge wasting rate, **Qw** can be calculated in m^3/d using the following equation with **TSS_W** being the TSS concentration in the wasted sludge:

$$Q_w = [(V*MLSS)/(SRT*TSS\_W)]$$

For U.S. units with total aeration tank volume, **V**, in ft^3 the sludge wasting rate, **Qw**, can be calculated in gal/d using the following equation:

$$Q_w = [(V*7.48*MLSS)/(SRT*TSS\_W)]$$

6. Calculate F/M and Volumetric BOD Loading							
F/M =	0.12	lb BOD/d/lb MLVSS		Vol. BOD Loading =	51.58	lb BOD/d/1000 ft^3	
7. Calculate Sludge Wasting Rate							
Waste A.S. Rate, **Q$_w$** =	23,785	gal/day					

Figure 11. Calculation of F/M, Volumetric BOD loading, and Sludge Wasting Rate

Oxygen/Air Requirement and Blower Calculations will be made using the "Rule of Thumb" guidelines shown below, which are made available by Sanitaire, a manufacturer of aeration diffusers.

Rules of Thumb for Estimating Oxygen/Air Requirements for Coarse or Fine Bubble Diffusers

Source:

1. The typical AOR/SOR (or AOTE/SOTE) is 0.50 for a coarse bubble aeration system.
2. The typical AOR/SOR (or AOTE/SOTE) is 0.33 for a fine bubble aeration system.
3. The typical SOTE is 0.75% per foot (2.46%/m) of diffuser submergence for a coarse bubble system
4. The typical SOTE is 2.0% per foot (6.56%/m) of diffuser submergence for a fine bubble system
5. 1 SCF of air weighs 0.075 lb/ft^3 (1.20 kg/m^3) and contains 23% oxygen by weight, thus:
6. Air contains 0.0173 lbm of oxygen per SCF (0.2770 kg oxygen/SCM)
7. For biological treatment with SRT from 5 to 10 days, lb oxygen required /lb BOD removed is typically in the range from 0.92 - 1.1 lb O_2/lb BOD. Higher SRT results in a higher value of lb O_2 required/lb BOD removed.
8. The oxidation of 1 lb of ammonia nitrogen typically requires 4.1 to 4.6 lb of oxygen.

Figure 12 shows the S.I. version of user inputs needed to make the oxygen/air/blower calculations using the "Rule of Thumb" guidelines shown above. **Figure 13** shows the U.S. version.

8. Oxygen/Air Requirement and Blower Calculations (for the Aeration Tank)

i) INPUTS (Values of "Rule of Thumb" Constants for the Calculations - See info at right)

O_2 needed per kg BOD =	1.50	kg O_2/kg BOD	Depth of Diffusers =	4.4	m
O_2 needed per kg NH_4-N =	4.57	kg O_2/kg NH_4-N	Standard Temperature =	20	°C
SOTE as Function of Depth =	6.56%	% per m depth	Standard Pressure =	1.014	bar
AOTE/SOTE =	0.33		Atmospheric Pressure =	1.014	bar
Press. Drop across Diffuser =	0.030	bar	Air Density at STP =	1.200	kg/m^3
(from mfr/vendor)			O_2 Content in Air =	0.2770	kg/m^3

Figure 12. User Inputs for Oxygen/Air/Blower Calculations – S.I. Version

8. Oxygen/Air Requirement and Blower Calculations (for the Aeration Tank)

i) INPUTS (Values of "Rule of Thumb" Constants for the Calculations - See info at right)

O_2 needed per kg BOD =	1.50	lb O_2/lb BOD	Depth of Diffusers =	14.5	ft
O_2 needed per kg NH_4-N =	4.57	lb O_2/lb NH_4-N	Standard Temperature =	68	°F
SOTE as Function of Depth =	2.00%	% per ft depth	Standard Pressure =	14.7	psi
AOTE/SOTE =	0.33		Atmospheric Pressure =	14.7	psi
Press. Drop across Diffuser =	12.0	in W.C.	Air Density at STP =	0.075	lbm/SCF
(from mfr/vendor)			O_2 Content in Air =	0.0173	lbm/SCF

Figure 13. User Inputs for Oxygen/Air/Blower Calculations – U.S. Version

The results of the oxygen/air requirement and blower calculations are shown for S.I units in **Figure 14** and for U.S. units in **Figure 15**.

ii) Calculations

Press. at mid depth, P_D =	1.2	bar		NH_3-N Removal Rate =	7.9	kg/hr
BOD Removal Rate =	63	kg/hr		AOTE =	9.5%	
Oxygen Requirement =	130.5	kg/hr		Air Requirement =	82	SCMM
SOTE =	29%			Blower Outlet Pressure =	1.5	bar
(This is the air flow rate needed for the aeration tank,						
typically provided by a fine bubble diffuser system.)						

Figure 14. Oxygen/Air Requirement/Blower Calculations – S.I. Version

ii) Calculations

Press. at mid depth, P_D =	17.8	psi		NH_3-N Removal Rate =	17.3	lb/hr
BOD Removal Rate =	139	lb/hr		AOTE =	9.6%	
Oxygen Requirement =	287.6	lb/hr		Air Requirement =	2895	SCFM
SOTE =	29%			Blower Outlet Pressure =	21.4	psia
(This is the air flow rate needed for the aeration tank,						
typically provided by a fine bubble diffuser system.)						

Figure 15. Oxygen/Air Requirement/Blower Calculations – U.S. Version

The calculations in this section are rather straightforward. The **pressure at mid depth** is the (diffuser depth/2) times the specific weight of water with unit conversions as needed. The **BOD removal rate** is the ww flow rate times the (influent BOD minus the target effluent BOD) with unit conversions as needed. The **NH₃-N removal rate** is the ww flow rate times (the influent TKN minus the target effluent NH₃-N). Again, unit conversions are needed. The **rate of oxygen requirement** in lb/hr or kg/hr is calculated as the **BOD removal rate** times the mass of O_2 needed per mass of BOD removed plus the **NH₃-N removal rate** times the mass of O_2 needed per mass of NH₃-N removed. The **SOTE** (standard oxygen transfer efficiency) is calculated as the diffuser depth times the specified % per unit depth for SOTE. The **AOTE** (actual oxygen transfer efficiency) is calculated as **SOTE(AOTE/SOTE)**. The **Air Requirement** is calculated (in SCMM) as [(**oxygen requirement** in kg/hr/**AOTE**)/**O₂ content in air** in kg/m^3]/60. To calculate the **Air requirement** in SCFM, the **oxygen requirement** will be in lbm/hr, and the **O₂ content in air** will be in lbm/SCF.

Calculation of Alkalinity Requirements is illustrated in **Figure 16** (S.I. units) and **Figure 17** (U.S. units). The equations used for those calculations are as follow:

Alkalinity used for Nitrification = 7.14(NOx)   (mg/L as $CaCO_3$)

Alk. Conc. needed = Alk. used for Nitrif. + Target Effl. Alk. - Alk$_o$ (mg/L as $CaCO_3$)

Alk. Flow needed = Q$_o$ (Alk. Conc. needed)/1000   (kg/day) - S.I. units

Alk. Flow needed = Q$_o$ (Alk. Conc. needed)*8.34   (lb/day) - U.S. units

Sodium Bicarbonate Flow needed =
(Alk. Flow needed)(Equiv Wt. of NaHCO₃)/(Equiv. Wt. of CaCO₃)

9. Calculate Alkalinity Requirement						
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 NH₃-N				
Calculations						
Alk. used for nitrification =	196.9	mg/L as $CaCO_3$				
Alkalinity needed =	136.9	mg/L as $CaCO_3$		Alkalinity needed =	1037	kg/day as $CaCO_3$
Sodium bicarbonate needed per day to maintain alkalinity =				1,742	kg/day NaHCO₃	

Figure 16. Calculation of Alkalinity Requirement – S.I. Version

9. Calculate Alkalinity Requirement

Input: Target Effluent Alkalinity = **80**   mg/L as CaCO₃

Constants needed for Calculations:

Equiv Wt. of CaCO₃ =	**50**	g/equiv.	Equiv Wt. of NaHCO₃ =	**84**	g/equiv.

Alkalinity used for Nitrification = **7.14**   g CaCO₃/g NH₃-N

Calculations

Alk. used for nitrification =	**196.8**	mg/L as CaCO₃			
Alkalinity needed =	**136.8**	mg/L as CaCO₃	Alkalinity needed =	**2281**	lb/day as CaCO₃

Sodium bicarbonate needed per day to maintain alkalinity = **3,833**   lb/day NaHCO₃

**Figure 17.** Calculation of Alkalinity Requirement – U.S. Version

7.   Process Design Calculations for Pre-Anoxic Denitrification

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. The nitrification reactions require an aerobic environment and the denitrification reactions require an anoxic environment (the absence of oxygen). The anoxic denitrification reactor may be either before the BOD removal/nitrification reactor (called pre-anoxic denitrification) or after the BOD removal/nitrification reactor (called post-anoxic denitrification). Only the pre-anoxic option will be discussed here. A flow diagram for an MBR process with   pre-anoxic denitrification is shown in **Figure 18** below.

In a pre-anoxic denitrification process, the BOD in the influent wastewater is used as the carbon source for denitrification.   In this process, however the influent wastewater entering the pre-anoxic reactor still has ammonia nitrogen present rather than the nitrate nitrogen needed for denitrification. A recycle flow from the aeration tank (identified as Internal Recycle in **Figure 20**) is used to send nitrate nitrogen to the denitrification reactor.
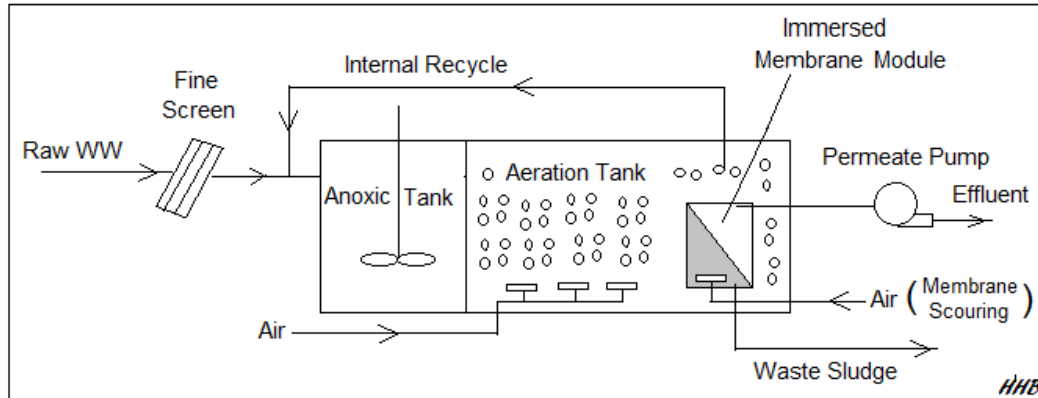
Figure 18. Flow Diagram for MBR Process with Pre-Anoxic Denitrification

Process Design for Pre-Anoxic Denitrification: These process design calculations will be for pre-anoxic denitrification basins to go with the BOD removal/nitrification aeration tanks that were sized in the previous section. The wastewater parameters/characteristics and biological kinetic coefficients used above will also be used here. Additional user inputs needed for process design of the pre-anoxic basins are shown in **Figure 19**. The values in **Figure 19** are for calculations in S.I. units. The3 U.S. version would have the freeboard specified as 1.5 ft, the liquid depth in the tank specified as 15 ft, and the mixing energy for the anoxic reactor would be 0.38 hp/10^3 ft^3. As noted at the bottom of **Figure 19**, a preliminary estimate for the anoxic detention time is needed for use in a later iterative calculation to zero in on its value.

Results of the first set of process design calculations are shown in **Figure 20**. The items calculated are the active biomass concentration, X_b, the internal recycle ratio, **IR**, the recycle flow rate to the anoxic tank, the NOx rate to the anoxic tank, the anoxic tank volume based on the estimated detention time, and the **F/M** ratio. The equations used for these calculations are as follows:

Active biomass conc: $X_b = [Q(SRT)/V][Y(S_o - S)/(1 + k_d(SRT))]$

Internal Recycle Ratio: $IR = (NO_x/N_e) - 1.0$

Recycle Flow rate to anoxic tank: $Q_{anox} = IR(Q)$

NOx feed rate = $(Q_{anox})(NOX_{IR})$ $F/M = QS_o/XV$

MBR Process Design Calculations - S.I. units

BOD Removal Nitrification, & PreAnoxic Denitrification

This worksheet makes the design calculations for preanoxic denitrification basin(s) to
go with the Aeration Tank(s) designed for BOD removal and Nitrification in Worksheet 4.
 (The wastewater parameters/characteristics and biological kinetic coefficients entered
  on Worksheet 2 will also be used in this worksheet.)

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

Inputs - Additional Design Parameters

			Mixing energy		
Nitrate conc. in IR =	6.0	mg/L	for anoxic reactor =	10	kW/10^3 m^3
Effl. nitrate conc. N_e =	6.0	mg/L	Design % Excess		
Temp. Coeff for **SDNR** =	1.026		Nitrif. Capacity =	20%	
Prelim. est. of det. Time, t_{an}:	0.233	hr	Liquid Depth in Tank =	5.0	m
Tank Freeboard =	0.5	m	Tank L:W ratio =	1.0	
Number of Anoxic Tanks =	3.0		(target L:W - only used if tank is rectangular)		

**NOTE: A preliminary estimate for anoxic detention time is needed in cell C14 to start an
iterative calculation of minimum anoxic detention time below.**

Figure 19. Additional User Inputs for Pre-Anoxic Denitrification Process Design
S.I. Version

Calculations - Preanoxic basin design for denitrification

1. Calculate active biomass concentration and IR ratio

Active biomass conc., X_b =	10,329	mg/L	IR ratio, **IR** =	3.6

2. Calculate feed rate of NO$_4$-N to anoxic tank and anoxic tank volume

Flow rate to anoxic tank =	27,231	m^3/d	NO$_X$ rate to anoxic tank =	163,384	g/day
(flow containing nitrate)			Anoxic tank volume, V_{an} =	74	m^3
			(based on detention time value in cell C14)		

3. Calculate the F/M ratio

Anoxic tank F/M ratio =	2.092	g BOD/d/g MLVSS

Figure 20. First Set of Calculations for Pre-Anoxic Denitrification Process Design -S.I.

The next set of calculations will determine the value of the **SDNR** (specific denitrification rate) and make use of that **SDNR** value to calculate the required anoxic tank volume and detention time. The **SDNR** has units of g NO_3-N/day/g biomass. It is the rate at which nitrate can be denitrified (removed) in grams per day per gram of biomass.

The calculated value for **SDNR** is based on Figure 8-23 in Metcalf & Eddy, *Wastewater Engineering, Treatment and Reuse*, 4th Ed. (Ref #1 at the end of the course). Figure 8-23 is a set of graphs that give SDNR as a function of **F/M** and **rbCOD/bCOD**. Values were read from these graphs and used to derive a set of equations for **SDNR** as a function of **F/M** and **rbCOD/bCOD**. Those derived equations are shown in **Table 3** below.

Equations for SDNR as a function of F/M and rbCOD/bCOD	
1. For rbCOD/bCOD = 0.10:	$SDNR = -0.0761*(F/M)^2 + 0.263*(F/M) + 0.00636$
2. For rbCOD/bCOD = 0.20:	$SDNR = -0.0674*(F/M)^2 + 0.270*(F/M) + 0.00385$
3. For rbCOD/bCOD = 0.30:	$SDNR = -0.0608*(F/M)^2 + 0.278*(F/M) + 0.00149$
4. For rbCOD/bCOD = 0.40:	$SDNR = -0.0591*(F/M)^2 + 0.289*(F/M) + 0.000536$
5. For rbCOD/bCOD = 0.50:	$SDNR = -0.0558*(F/M)^2 + 0.300*(F/M) + 0.00268$

Table 3. Equations for SDNR as a Function of F/M and rbCOD/bCOD

Figure 21 shows the results of the calculation of the **SDNR** and required anoxic tank volume and detention time. Note that an iterative calculation is needed as described in blue at the bottom of **Figure 21**, to calculate the required Anoxic Tank Volume and Detention Time.

4. Calculate the SDNR

rbCOD/bCOD ratio =	0.298		Next lower rbCOD/bCOD value from table:		0.2	
			Next higher rbCOD/bCOD value from table:		0.3	

SDNR for rbCOD/bCOD =	0.2	is equal to:	0.2742
SDNR for rbCOD/bCOD =	0.3	is equal to:	0.3178

SDNR for rbCOD/bCOD = 0.298   is equal to: 0.3168   g NO_3-N/day/g biomass   (at 20°C)

at T_{ww}, SDNR =   **0.258**   g NO_3-N/day/g biomass   (at T_{ww})

5. Calculate the Anoxic Tank Volume, Dimensions and Detention Time
        (User Input needed in Blue Cells)

NO_3-N reduction capacity =   196,065   g/d   % Excess Nitrif. Capacity: 20.0%

Difference between Design and Calculated % Excess Nitrification Capacity =   0.000

Goal Seek Result:

Anoxic Tank min. Vol., $\mathbf{V_{an}}$ =   **74** m^3 min. Anox. Det. Time, $\mathbf{t_{an}}$ =   **0.23**   hr

NOTE: This is an iterative solution. You must use Excel's "Goal Seek" to find the V_{an} vand t_{an} values as follows: Place the cursor on cell H51 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" H51 "To value:" 0, "By changing cell:" C14, and click on "OK". The calculated values of V_{an} and t_{an} will be in cells C53 and H53. Cell H51 should be zero if the process worked properly. A preliminary estimate for t_{an} is needed in cell C14 in order for the iterative solution to work.

Figure 21. Calc'n of **SDNR** and required Anoxic Tank Volume and Detention Time

The calculations for the values shown in **Figure 21** proceed as follows. **rbCODo** was a user specified value and **bCODo** was calculated as part of the BOD removal/nitrification process design calculations, so the ratio of those two can readily be calculated. Then If statements are used to find the two values of **rbCOD/bCOD** from **Table 4**, below, that bracket the calculated value. The VLOOKUP function is then used to populate the yellow cells in **Table 4** with the coefficients for the equations giving **SDNR** as a function of **F/M** at those two values of **rbCOD/bCOD**. Those coefficients are used to calculate the **SDNR** at each of the bracketing values of **rbCOD/bCOD** and interpolation is used to calculate the **SDNR** at 20°C for the **rbCOD/bCOD** value for this system. The SDNR at the specified wastewater temperature, Tww, is then calculated as: **SDNR at T_{ww} = (SDNR at 20°C)θ^{Tww-20}**. The value of θ to be used is the user specified value for the SDNR temperature correction coefficient.

Coefficients for SDNR Equation				
rbCOD/bCOD	Coeff. of F/M^2	Coeff. of F/M	Constant	
0.1	-0.0761	0.2625	0.0064	
0.2	-0.0674	0.2702	0.0039	
0.3	-0.0608	0.2784	0.0015	
0.4	-0.0591	0.2892	0.0005	
0.5	-0.0558	0.2996	0.0027	
0.20	-0.0674	0.2702	0.0039	
0.30	-0.0608	0.2784	0.0015	

Table 4. Coefficients for **SDNR** Equation

The denitrification capacity is calculated as: $V_{anox}(SDNR)(X_b)$

Note that X_b is the active biomass in the anoxic denitrification tank.

The % Excess Denitrification Capacity is then calculated using the denitrification capacity and the previously calculated NOx rate to the anoxic tank. Excel's Goal Seek function is then used to set the % Excess Denitrification Capacity equal to the User entered value by changing the anoxic detention time. This results in a minimum required anoxic tank volume and detention time.

Figure 22 shows the remaining calculated values for the pre-anoxic denitrification system. This includes the anoxic tank width and length, the reduced oxygen/air requirement due to the nitrate reduction oxygen credit, the reduced alkalinity requirement due to the alkalinity produced by denitrification, the anoxic tank mixing power needed, and the sludge wasting rate.

The oxygen credit for nitrate reduction is calculated as: $2.86\ Q_o(NO_x - N_e)$

The alkalinity produced by nitrate reduction is calculated as: $3.57(NO_x - N_e)$

The anoxic tank mixing power required is calculated as the anoxic tank volume times the user specified value for mixing power needed per unit volume.

The Sludge Wasting Rate is calculated as: $Q_w = (V*MLSS)/(SRT*TSS\_W)$

			Click on green box and then on			
Min. Vol. per tank, V_{tank} =	25	m^3	arrow to Select Tank Shape:		rectangular	
Calculated Tank Width =	2.2	m	**Actual Tank Width:**		2.5	m
Calculated Tank Length =	2.2	m	**Actual Tank Length:**		2.5	m
Tank Wall Height =	5.5	m	Actual Tank liquid Volume =		31.3	m^3
			(Pre-Anoxic Tank Volume)			
Anoxic Det'n time, τ =	0.3	hr				

6. Recalculate the oxygen/air requirement due to the nitrate reduction oxygen credit

Oxygen credit =	467	kg/day	=	19.5	kg/hr	
O_2 Utilization Rate =	111.1	kg/hr	Req'd air flow rate, SCMM =		70.2	SCMM
			Blower Outlet Pressure =		1.5	bar

7. Recalculate Alkalinity Requirement

Alkalinity produced =	77.0	mg/L as $CaCO_3$				
Alkalinity needed =	59.9	mg/L as $CaCO_3$	Alkalinity needed =		453	kg/day as $CaCO_3$
Sodium bicarbonate needed per day to maintain alkalinity =				762	kg/day $NaHCO_3$	

8. Calculate Anoxic tank mixing power needed

Anoxic Tank Mixing Power =	0.9	kW

9. Calculate Sludge Wasting Rate

Waste A.S. Rate, Q_w =	94	m^3/d

Figure 22. Final Set of Calculations for Pre-Anoxic Denitrification

8. Summary

The MBR (membrane bioreactor) process uses an aeration tank similar to those used in conventional activated sludge processes, combined with membrane filtration as a replacement for secondary sedimentation. This combination can produce a very high quality effluent, typically with a more compact reactor than conventional activated sludge, but requires a higher rate of aeration than conventional activated sludge in order to keep the membranes from fouling. The current typical MBR process configuration uses a membrane module submerged in the aeration tank.

This course includes discussion of process design calculations for the membrane module used in an MBR system, for an MBR aeration tank designed to provide BOD removal and nitrification, and for a pre-anoxic tank to go with an MBR BOD removal and nitrification system.

9. References

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