Module 4
Fixed Film Operational Strategies

SUNY Farmingdale
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BOD Removal in Fixed Film Processes

Heterotrophic bacteria hydrolyze organic-N to ammonium-N.

Heterotrophic aerobic bacteria utilize oxygen, organic material, ammonium-N, and ortho-P to produce carbon dioxide, water, and more bacterial cells.
Nitrification

\[ 2\text{NH}_4^+ + 3\text{O}_2 \rightarrow 2\text{NO}_2^- + 2\text{H}_2\text{O} + 4\text{H}^+ \]

Oxygen Required = 3.43 lb / lb N oxidized
Alkalinity Required = 7.14 lb as CaCO\(_3\) / lb N oxidized

\[ 2\text{NO}_2^- + \text{O}_2 \rightarrow 2\text{NO}_3^- \]

Oxygen Required = 1.14 lb / lb N oxidized

For both reactions together:
Total Oxygen Requirement = 4.57 lbs / lb N oxidized
Total Alkalinity Requirement = 7.14 lbs as CaCO\(_3\) / lb N oxidized
Factors Affecting Nitrification

What Factors Affect Nitrification in Fixed Film Processes?
Factors Affecting Nitrification in Fixed Film Processes

- BOD loading rate
- Ammonia loading rate
  - Per unit surface area
  - Per unit volume
- Dissolved oxygen
- Hydraulic loading rate
- Recirculation
- Temperature
- pH
- Alkalinity
- Inhibitory compounds
- Predator growth
BOD Loading Rates for Carbonaceous BOD Removal in the Trickling Filter or RBC Process

- **Trickling Filter Loading Rate**
  - 25 lbs BOD$_5$ / day / 1000 cu ft (rock media)
  - 1.7 lbs BOD$_5$ / day / 1000 sq. ft.

- **RBC Loading Rate**
  - 1.0 to 2.0 lbs / day / 1000 sq. ft.
BOD Loading Rates for Nitrification in the Trickling Filter or RBC Process

- **Trickling Filter Loading Rate**
  - 5 lbs BOD$_5$ / day / 1000 cu ft (rock media)
  - 0.3 lbs BOD$_5$ / day / 1000 sq. ft.

- **RBC Loading Rate**
  - 0.8 lbs BOD$_5$ / day / 1000 sq. ft.
Definitions

Heterotroph - Organism which uses organic matter for energy and growth. The BOD-removers and denitrifiers in BNR systems are heterotrophic organisms

Autotroph - Organism which uses inorganic matter for energy and growth. The nitrifiers in BNR systems (nitrosomonas and nitrobacter) are autotrophic organisms
Competition Between Heterotrophs and Autotrophs

• Heterotrophs (BOD-removers) have competitive advantage over autotrophs (nitrifiers)
• Heterotrophs grow at head end of TF or RBC, autotrophs grow at tail end
• Soluble BOD$_5$ must drop below about 15 mg/L to allow nitrifiers to grow
Dissolved Oxygen

- As dissolved oxygen increases, nitrifier growth rate increases
- Oxygen available to nitrifiers is affected by turbulence and diffusion into biofilm
- DO concentration often masks pH and temperature effects
- At temperatures above 15°C dissolved oxygen is often the rate limiting parameter
- Forced ventilation for TFs or aerated RBCs can increase nitrification rate
DO Depletion in Biofilm

![Diagram showing DO depletion in biofilm.](image)

- **Media Surface**
- **Biofilm Surface**
- **Bulk Liquid**

**Distance (mm)**

**Concentration (mg/L)**

- 1.0 mm

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
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<tr>
<td>2</td>
<td>1</td>
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<tr>
<td>2</td>
<td>1</td>
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Module: 4
Unit: 1
Transparency: 1-10
Hydraulic Loading Rate - Trickling Filters

• Typical 25 - 200 gpd per sq. ft. of trickling filter plan area
• Past studies indicated importance of recirculation rate in Trickling Filters
• More recent studies have indicated no significant benefit from recirculation as long as sufficient wetting is provided
• Use 1:1 recirculation directly around trickling filter
• Some studies have shown benefits from slowing down distributor, other studies have shown no benefit to slowing distributor
SK Approach

SK = \frac{(Q+R)(1.337 \times 10^5 \text{ cu. ft./mil.gal.})(304.8 \text{ mm/ft})}{(A)(a)(n)(1440 \text{ min/d})}

SK = flushing intensity, mm/pass of an arm
Q+R = average flow to trickling filters, mgd
A = total trickling filter plan area, sq. ft.
a = number of arms
n = rpm

Adapted from WEF MOP 8, 1992, p. 695, Equation (3)
## Suggested SK Values

<table>
<thead>
<tr>
<th>BOD5 Loading (lb/d/1000 cu.ft.)</th>
<th>Design SK mm/pass</th>
<th>Flushing SK mm/pass</th>
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<tbody>
<tr>
<td>16</td>
<td>10-100</td>
<td>&gt;200</td>
</tr>
<tr>
<td>31</td>
<td>15-150</td>
<td>&gt;200</td>
</tr>
<tr>
<td>62</td>
<td>30-200</td>
<td>&gt;300</td>
</tr>
<tr>
<td>125</td>
<td>40-250</td>
<td>&gt;400</td>
</tr>
<tr>
<td>187</td>
<td>60-300</td>
<td>&gt;600</td>
</tr>
<tr>
<td>250</td>
<td>80-400</td>
<td>&gt;800</td>
</tr>
</tbody>
</table>

Adapted from WEF MOP 8, 1992, p. 697, Table 12.4
Hydraulic Loading Rate - RBCs

- Typical 1 - 3 gpd per sq. ft. of media surface area
- Recirculation is not normally necessary in RBC systems
- In aerated RBCs of SBCs, can provide a return sludge stream and develop some suspended growth in RBC basin
- Recirculation of RBC effluent in nitrifying systems may provide some denitrification
Competing Effects of Increasing Temperature

Increases BOD Uptake Rate
- Reduces BOD in Bulk Phase
- Increases Nitrification Rate

Increases Nitrifier Growth Rate
- Increases Nitrification Rate

Decreases Solubility of Oxygen in Water
- Reduces Oxygen Transfer into Biofilm for Same Air Flow
- Decreases Nitrification Rate Unless Air Flow Rate Increased

Result - Often no temperature effect is observed between 15°C and 20°C
Effect of pH and Alkalinity on Nitrification

Nitrification consumes alkalinity and lowers pH of the wastewater

pH below 6.5 or above 8.0 can significantly inhibit nitrification.

Rules of Thumb:
Maintain pH in the range 6.5 - 8.0 for optimum nitrification.

Overall alkalinity consumption is generally less than the theoretical 7.14 lbs as CaCO$_3$ per lb of ammonia-N nitrified.
Simplified Calculation of Alkalinity Requirement for Nitrification

Given:
- Plant Influent Flow = 10 mgd
- Primary Effluent TKN = 31.5 mg/l

Alkalinity Consumed by Nitrification:

In lbs/day

\[(10 \text{ mgd}) \times (31.5 \text{ mg/l}) \times (7.14) \times (8.34) = 18,757 \text{ lbs alkalinity as CaCO}_3 \text{ per day}\]

In mg/l

\[(31.5 \text{ mg/l}) \times (7.14) = 225 \text{ mg/l alkalinity as CaCO}_3 \text{ consumed}\]
### Sources of Alkalinity

<table>
<thead>
<tr>
<th>Source</th>
<th>Form Delivered</th>
<th>lbs. Alkalinity as CaCO₃ per lb. or gallon of Product</th>
<th>Cost per lb. of Alkalinity as CaCO₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrated Lime</td>
<td>50 lb. Bags, 20 Ton Truck</td>
<td>1.33 per lb.</td>
<td>$0.074 (50 lb. Bag), $0.05 (20 Ton Truck)</td>
</tr>
<tr>
<td>Sodium Bicarbonate</td>
<td>50 lb. Bags</td>
<td>1.19 per lb.</td>
<td>$0.36</td>
</tr>
<tr>
<td>Sodium Hydroxide (Caustic Soda)</td>
<td>55 Gallon Drum, ½ Truck (1,750 Gallons), Full Truck (3,500 Gallons)</td>
<td>7.87 per gallon, 7.87 per gallon</td>
<td>$0.19 (55 Gallon Drum), $0.125 (½ Truck), $0.104 (Full Truck)</td>
</tr>
</tbody>
</table>
# Compounds Which Inhibit Nitrification

## Organic Compounds:
- Acetone
- Carbon Disulfide
- Chloroform
- Ethanol
- Monoethanolamine
- Phenol
- Ethylenediamine
- Hexamethylene Diamine
- Aniline

## Metals and Inorganic Compounds:
- Zinc
- Free Cyanide
- Perchlorate
- Copper
- Mercury
- Chromium
- Nickel
- Silver
- Cobalt
- Thiocyanate
- Sodium Cyanide
- Sodium Azide
- Hydrazine
- Sodium Cyanate
- Potassium Chromate
- Cadmium
- Arsenic (trivalent)
- Fluoride
- Lead
Denitrification

Nitrate $+\rightarrow$ Methanol $\rightarrow$ Carbon Dioxide $+\rightarrow$ Nitrogen Gas $+\rightarrow$ Water $+\rightarrow$ Hydroxide

$$6\text{NO}_3^- + 5\text{CH}_3\text{OH} \rightarrow 5\text{CO}_2 + 3\text{N}_2 \uparrow + 7\text{H}_2\text{O} + 6\text{OH}^-$$

Methanol Utilized = 1.9 lbs methanol per lb nitrate-N denitrified
This is equivalent to 2.86 lbs COD utilized per lb nitrate-N denitrified
Alkalinity produced = 3.57 lbs as CaCO$_3$ per lb nitrate-N denitrified

$$2\text{NO}_3^- + 2\text{H}^+ \rightarrow \text{N}_2 \uparrow + \text{H}_2\text{O} + 2.5\text{O}_2$$

Oxygen recovered = 2.86 lbs per lb nitrate-N denitrified
Simplified Calculation of Oxygen and Alkalinity Recovered by Denitrification

Given:
Plant Influent Flow = 10 mgd
Nitrate to be Denitrified

<table>
<thead>
<tr>
<th>Oxygen Recovered</th>
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</thead>
<tbody>
<tr>
<td>(10 mgd) x (22 mg/l) Nitrate-N lbs O\textsubscript{2} recovered per day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x 2.86 x 8.34 = 5,248 lbs O\textsubscript{2} recovered per day</td>
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</table>

<table>
<thead>
<tr>
<th>Alkalinity Recovered</th>
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<tbody>
<tr>
<td>(10 mgd) x (22 mg/l) Nitrate-N lbs alkalinity as CaCO\textsubscript{3} recovered per day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x 3.57 x 8.34 = 6,550 lbs alkalinity as CaCO\textsubscript{3} recovered per day</td>
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</tr>
</tbody>
</table>
Potential Aeration Power Savings Due to Denitrification

Assumptions:
- Activated Sludge Plant with Primary Clarifiers
- Plant Influent Flow = 10 mgd
- Plant Influent TKN = 35 mg/l
- Plant Influent BOD$_5$ = 180 mg/l
- Power Costs = $0.10 per kW-hr.

- With Denitrification
  - Fine Bubble Diffusers: $90,000
  - Coarse Bubble Diffuser: $155,000
  - Mechanical Aerators: $115,000

- Without Denitrification
Effect of Dissolved Oxygen on Denitrification

- Dissolved oxygen inhibits denitrification.

- As DO increases, denitrification rate decreases.

- To achieve denitrification, the nitrified wastewater must be subjected to anoxic conditions. This can happen to some extent within the biofilm.
Effect of Dissolved $O_2$ on Denitrification Rate

Maximum Specific Denitrifier Growth Rate

$$\mu_D = \mu_{\text{max},D}(0.1/(0.1*\text{DO}))$$
As temperature increases, denitrifier growth rate increases.

\[ T \uparrow \quad \mu_D \uparrow \]
Effect of Temperature on Denitrification Rate

Denitrifier Growth Rate

\[ \mu_D = \mu_{\text{max}, D} 1.08^{(T-20)} \]
Effect of pH on Denitrification Rate

• Denitrifiers are generally less sensitive to pH than nitrifiers.

Rule of Thumb:
• If pH is within the recommended range of 6.5 - 8.0 for nitrification, there will be no pH effects on denitrification.
Effects of Inhibitory Compounds on Denitrification

- Denitrifiers are generally less sensitive to inhibitory compounds than nitrifiers.

- If there are no compounds present which inhibit nitrification, there will probably be no inhibition of denitrification.
Effects of Available Carbon Source on Denitrification

- Denitrification rate varies greatly depending upon the source of available carbon.
  - Highest rates are achieved with addition of an easily-assimilated carbon source such as methanol.
  - Lower denitrification rate is achieved with raw wastewater or primary effluent as the carbon source.
  - Lowest denitrification rate is observed with endogenous decay as the source of carbon.
Effect of Biodegradable SCOD in Anoxic Zone on Specific Denitrification Rate

Range of Variation of Ks
Ks = 20-50 mg/L SCOD at 12°C

T = 20°C
DO < 0.05
So, what do we need to do to get my plant to nitrify?
Conversion and Operation of Plants for Nitrification

So, what do we need to do to get my plant to nitrify?

Create a fixed film loading rate conducive to nitrification, and provide sufficient oxygen for nitrification.
Methods to Decrease Loading Rate

- Activate trickling filter or RBC by adding a return sludge line

- Increase surface area of media in existing unit
  - Replace rock TF media with plastic media
  - Increase RBC media density

- Add a new biological treatment unit
  - Tertiary trickling filter
  - Additional RBC
  - Nitrification filter
Methods to Increase Surface Area

- Change Size of Media

Reduce Size of Media
Increases Surface Area

Surface Area \( \left( \frac{m^2}{m^3} \right) = \frac{\pi}{\text{DIAMETER (in m)}} \)

Surface Area \( \left( \frac{\text{ft}^2}{\text{ft}^3} \right) = \frac{\pi}{\text{DIAMETER (in feet)}} \)

PROBLEM: Calculate surface area per unit volume of a filter with rock media with a diameter of 150 mm (~ 6 inches) and shale with a diameter of 5 mm.
Convert Rock Media Trickling Filters to Plastic Media

Trickling Filter

Primary Effluent

Recirculation

To Secondary Clarifier

Trickling Filter

Module: 4
Unit: 2
Transparency: 2-4
Effects of Conversion to Plastic TF Media

- Higher Surface Area Per Unit Volume
- More Void Space - Better Oxygen Transfer
- Higher Volume for a Footprint - Taller Filters, Lighter Media

Should First Stage Filters for BOD Removal Also Use Plastic Media?
How Thick Should the Biofilm Be?
How Do We Control Thickness?
Trickling Filter Followed by RBCs

- Trickling Filter
- Rotating Biological Contactors
- Secondary Clarifier

Primary Effluent
Recirc
RAS
Secondary Sludge
Secondary Effluent
Trickling Filter Solids Contact Process

Trickling Filter

Solids Contact Basin

Secondary Clarifier

Secondary Effluent

Primary Effluent

Recirculation

RAS

WAS
Trickling Filter Followed by Nitrifying Filter

1. Trickling Filter
2. Secondary Clarifier
3. Nitrification Filter

Flow Diagram:
- Primary Effluent
- Secondary Sludge
- Recirc
- RAS
- Secondary Effluent
Evaluation of TF or RBC Loading Rate

• Determine specific surface area of media
• Determine total surface area of media
• Determine BOD$_5$ loading rate
• Compare loading rate to standard rates
### Determine Specific Surface Area

- **Rock media (1” - 3”)**  19 ft²/ft³
- **Rock media (2” - 4”)**  14 ft²/ft³
- **Surfpac X-Flo 30**  30 ft²/ft³
- **Surfpac X-Flo 42**  42 ft²/ft³
- **Brentwood Accu-Pac CF-3000**  31 ft²/ft³
- **Brentwood Accu-Pac CF-1900**  48 ft²/ft³
- **Brentwood Accu-Pac CF-1200**  69 ft²/ft³
- See manufacturer’s data sheet for other manufactured media
Determine Total Media Surface Area

Total Media Area (ft²) =

Specific Surface Area (ft²/ft³) \times \text{Total Media Volume (ft}^3)\text{)}
Determine $BOD_5$ Loading Rate

$$BOD_5 \text{ Loading Rate (lbs/1000 ft}^2\text{/day)} = \frac{\text{TF or RBC Influent } BOD_5 \text{ (lbs/d)}}{\text{Total Media Surface Area (1000 ft}^2\text{)}}$$
Evaluate Loading Rate

Is BOD5 loading less than 0.4 lb/d/1000 ft²?

Yes → Plant will nitrify partially or completely at 10°C or higher

No → Is BOD5 loading in range 0.4 to 4.0 lb/d/1000 ft²?

Yes → Plant will nitrify partially at warm temperatures

No → Plant will not nitrify with existing media surface area
Trickling Filter Media Replacement

See worksheet
Methods to Increase Dissolved Oxygen

- Provide forced ventilation for trickling filters
- Increase hydraulic loading rate in trickling filters
- Replace trickling filter media with media with a greater void ratio
- Add diffused air in RBCs
Biological Aerated Filters

- Can be used as an add-on nitrifying filter when existing process cannot be made to nitrify
- Upflow or downflow configuration
- Various media including sand, shale, polystyrene
Now that my plant is nitrifying, what do I need to do to make it denitrify?
Now that my plant is nitrifying, what do I need to do to make it denitrify?

Establish anoxic conditions somewhere in the biological process.
Methods to Achieve Denitrification

- Incidental denitrification in trickling filter or RBC with recycle
- Convert a portion of existing unit to anoxic zone
- Add a new denitrification filter downstream of the nitrifying process
Preliminary Evaluation of Denitrification Alternatives

- Can existing unit nitrify or partially nitrify?  
  - **Yes**: Try generating anoxic conditions through submergence or generating low DO.  
  - **No**: Add new nitrification and denitrification units.

- If existing unit cannot nitrify, ask:  
  - Is there capacity to sacrifice some existing volume for denitrification?  
    - **Yes**: Add new denitrification unit.  
    - **No**: Add new nitrification and denitrification units.
Incidental Denitrification

Primary Effluent

Trickling Filter

Recirculation

Trickling Filter

To Secondary Clarifier

Module: 4
Unit: 3
Transparency: 3-4
Establishing an Anoxic Zone

Trickling Filter

Primary Effluent

Rotating Biological Contactors

Anoxic zone

Recirc

Secondary Clarifier

Secondary Effluent

Secondary Sludge

RAS

Module: 4
Unit: 3
Transparency: 3-5
Trickling Filter Followed by Nitrifying and Denitrifying Filters

Trickling Filter

Secondary Clarifier

Nitrification Filter

Denitrification Filter

Primary Effluent

Recirculation

Secondary Sludge

Methanol

Secondary Effluent

Module: 4
Unit: 3
Transparency: 3-6
Denitrification Filters

- Can be used as an add-on denitrifying filter when existing process cannot be made to denitrify
- Upflow or downflow configuration
- Various media including sand, shale, polystyrene
- Methanol addition for carbon source
COD Depletion in Biofilm

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Concentration (mg/L)</th>
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</thead>
<tbody>
<tr>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
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SCOD biodegradable
Ammonia Depletion in Biofilm

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<th>Distance (mm)</th>
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<tr>
<td>4</td>
<td>2</td>
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<td>6</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>NH₄⁺-N</td>
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Module: 4
Unit: 3
Transparency: 3-9
Nitrate Profile in Biofilm

Biofilm with some Nitrification

Distance (mm)
Concentration (mg/L)

NO$_x$-N
Biofilm Profiles
Fixed Film Discussion

• Contact Between Biofilm Surface and Liquid Flowing Through the Filter.
  – How Good Is the Contact?
  – Is It One Form?
  – How Do We Improve It?

• Thickness of Stagnant Liquid Layer
  – Should We Reduce Thickness?
  – How Is Biofilm Sloughing Affected?

• Thickness of Biofilm
  – A. Submerged Filters Vs. “Exposed to Air Filters”
  – B. Upflow Vs. Downflow