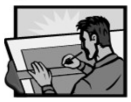
Process Control for Wastewater Operators
"Understanding the Process"



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PART 1
Activated Sludge Process
Performance Standards

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- *Read Slides from Left to Right*
- *If printed 6 slides per page*

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Before We Begin

Look Over Handouts

- _HO1 PC for WW Operators Parts 1 & 2 — 32 pages
- _HO2 PC Worksheets with Examples — 24 pages
- _HO3 BNR/ENR Selector Setup — 2 pages
- _HO4 Process Performance Standards — 1 page
- _HO5 AS Operator Skill Set Survey — 2 pages
- _HO6 Workgroup Problem No7 — 4 pages
- _HO7 Workgroup Problem No8 — 3 pages

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Today's Class
What to Expect

- Course is intended for Intermediate Level WWTP Operators of Activated Sludge Processes
- New WWTP Operators will also benefit but may not be able to pass Post Exam and receive 10.5 hours of credit. But will receive 7 hours of credit.

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What We Will Cover

- Operational parameters and Design Standards used for Process Control and Troubleshooting.
- Use of Regional Standards (10 States) to evaluate Activated Sludge Processes and their final clarifiers.
- Google "10 States Standards Wastewater"
  - 2014 10 States Standards (current edition)
  - MD 2021 Wastewater Design Guidelines
  - A. S. Process Performance Standards

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What We Will Cover

- Worksheets used for calculating operational parameters then comparing them to Process Performance Standards.
- A short math review
- Worksheets for Aeration Basins & Selectors
  - MLSS and MLVSS pounds
  - Organic Loading Rate (OLR) and F/M Ratio
  - Sludge Age and Sludge Volume Index (SVI)
  - Solids Retention Time (SRT)

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What We Will Cover

- Worksheets for Final Clarifiers
  - Detention Time (DT)
  - Surface Overflow Rate (SOR)
  - Surface Loading Rate (SLR)
- Worksheet Example
  - Solids Loading Rate (SLR), ppd/Sq. Ft.
- Process Control for Smaller WWTPs
- Process Control for Larger WWTPs

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What We Will Cover

- Biological Nutrient Removal (BNR) and Enhanced Nutrient Removal (ENR)
- Typical 5-Stage Bardenpho Process Selector Setup
- Example Calculations for using Process Control Worksheets
- Course Evaluations
- Post Test Exam (20 questions)

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Part 1 Activated Sludge Process Performance Standards

- Performance Standards for Aeration Basins
  - Detention Time (DT)
  - Organic Loading
    - Organic Loading Rate
    - Food to Microorganism Ratio (F/M)
- Sludge Age (SA and MCRT vs. SRT)
  - MCRT – Mean Cell Resident Time
  - SRT – Solids Retention Time

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Part 1 Activated Sludge Process Performance Standards

- Performance Standards for Secondary Clarifiers
  - Detention Time (DT)
  - Weir Overflow Rate (WOR)
  - Surface Overflow Rate (SOR)
  - Solids Loading Rate (SLR)

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Part 1 Activated Sludge Process Performance Standards

- Activated Sludge Processes
  - Conventional Activated Sludge
  - Extended Aeration and Nitrification
  - Sequencing Batch Reactors
  - BNR and ENR
  - Discussion of Process Control

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Part 1 Activated Sludge Process Performance Standards

- Performance Standards
  - Used by Engineers for Design and Review of Activated Sludge Processes
  - Defines an Activated Sludge Process
  - Provides Guidelines and Operational Targets for Process Control

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Part 2 Process Control Worksheets

In Part 2 we'll discuss the use of Process Performance Standards and other Process Control Tools commonly used by Operators of Activated Sludge Plants.

Process Control Worksheets will be provided to reduce classroom emphasis on math and allow for a greater focus on Process Control.

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Aeration Basins and Selectors

- Process Control Parameters for Aeration Basins and Selectors
  - **Detention Time in Hours**
  - **Organic Loading Rate**
  - **Food to Microorganisms (F/M) Ratio**
  - **Sludge Age**
    - SA – Sludge Age
    - MCRT – Mean Cell Resident Time
    - SRT – Solids Retention Time

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Detention Time (DT)

- The average time a gallon of water remains in specified tank, basin, or process
- *Capacity divided by flow*
- A measurement of hydraulic loading on a given tank or basin.
- Used for aeration basins, BNR basins, clarifiers and other units.

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Aeration Basins and Selectors

- Detention Time (DT) (continued)
  - DT is in hours for basins and clarifiers
    - Influent flow (or forward flow) is used
    - In sludge re-aeration basins return sludge flow is used, which is the influent flow to these basins

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Process Performance Standards

- Detention Time (DT) (continued)
  - DT for Aeration Basins will range from 1 to 24 hours (flow-thru process)
    - DT is one of the parameters used to identify or classify activated sludge processes.
    - Operators usually use Average Daily Flow (ADF) and will compare DT to plant design criteria

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Process Performance Standards

- Detention Time (DT) (continued)
  - High-Rate Processes 1 to 5 hours
  - Conventional 6 to 8 hours
  - Nitrifying basins 12 or more hours
  - Extended Aeration Basins around 24 hours

Remember the process must Nitrify before it can De-Nitrify.

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DT, hours =

$$\frac{\text{Capacity x 24 hrs.}}{\text{Flow}}$$

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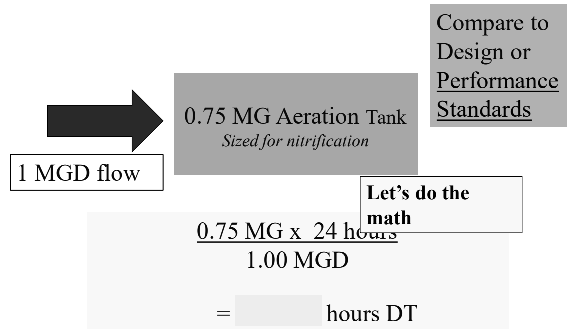
Detention Time (DT)



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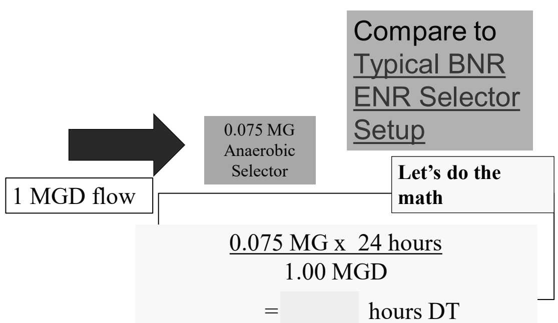
Detention Time (DT)



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Detention Time for Aeration Basins and Selectors

- Detention Time (DT) (continued)
  - As a troubleshooting and process control tool, Operators will calculate DT for aeration or selector basins and compare it to plant design or industry standards
  - Used to define mode of operation such as Conventional vs. Nitrification vs. Extended Aeration

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Organic Loading and F/M Ratio

- Aeration Basins and Oxic Selectors are also sized or classified by Organic Loading
  - Pounds per Day of BOD/1000 cu. ft.
- and F/M Ratio
  - Pounds per Day of BOD / # MLVSS

(MLVSS) - Mixed Liquor Volatile Suspended Solids

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Organic Loading =

(for Aeration Basins and Oxic Selectors)

$$\frac{\text{pounds per day of BOD}}{\text{1,000 cubic feet of capacity}}$$

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Organic Loading

Compare to Design or Performance Standards

1 MGD flow
300 mg/L BOD

0.75 MG Aeration Tank
Sized for nitrification
100,267 cubic feet
100.3 (1000 cu. ft.)

Let's do the math

300 mg/L x 8.34 x 1 MGD = 2502 ppd BOD

$$\frac{2502 \text{ ppd BOD}}{100.3 \text{ (1000 cu. ft.)}}$$

= ppd / 1000 cu. ft.

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Food to Microorganisms (F/M) Ratio =

$$\frac{\text{pounds per day of BOD}}{\text{Pounds of MLVSS}}$$

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F/M Ratio

Compare to Design or Performance Standards

1 MGD flow
300 mg/L BOD

0.75 MG Aeration Tank
Sized for nitrification
3,500 mg/L MLVSS

3,500 mg/L x 8.34 x 0.75 MG = 21,892 pounds of MLVSS

300 mg/L x 8.34 x 1 MGD = 2,502 ppd BOD

Let's do the math

$$\frac{2{,}502 \text{ ppd of BOD}}{21{,}892 \text{ pounds of MLVSS.}}$$

= F/M Ratio

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Sludge Age

In the earlier days of wastewater treatment, the Sludge Age formula was commonly use by operators to calculate and monitor Sludge Age.

For the most part, today the term "Sludge Age" is used as a general term for monitoring and controlling the age and concentration of MLSS.

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Sludge Age (from Years Ago)

Sludge Age (SA) Formulas

$$SA = \frac{\text{pounds of MLSS under aeration}}{\text{ppd of TSS entering aeration}}$$

or

Preferred

$$SA = \frac{\text{pounds of MLVSS under aeration}}{\text{ppd of TSS entering aeration}}$$

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Sludge Age

Although not used much today, a few Operators of smaller WWTPs may still be using it.
When smaller domestic and industrial WWTPs have inconsistent wasting rates their Operators may utilize one of the Sludge Age formulas.

However, today for most WWTPs the SRT or MCRT formula is recommended for monitoring sludge age.

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Mean Cell Retention Time (MCRT) and Solids Retention Time (SRT) Formulas

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MCRT vs. SRT

- For years now the SRT and MCRT formulas have been confused and/or considered the same.
- In Maryland, MDE uses the ABC Formula Sheet which defines SRT and MCRT as both using aeration and clarifier capacity.
- New WEF manuals are defining SRT and MCRT as shown here.

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(WEF) MCRT Formula

- **MCRT**
  - (MCRT) Mean Cell Resident Time

MLSS, lbs under aeration **+ solids in Clarifier**
lbs SS wasted + lbs SS lost in effluent

= _______ Days

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(WEF) SRT Formula

- **SRT**
  - (SRT) Solids Retention Time

MLSS, lbs under aeration
lbs SS wasted + lbs SS lost in effluent

= ______ Days

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MCRT vs. SRT

Example WWTP
1 MGD Flow
Aeration Capacity 0.75 MG
Clarifier Capacity 0.25 MG
MLSS 3,000 mg/L
WSSS 7,000 mg/L @ 0.04 MGD
5 mg/L Effluent TSS

Let's use the above information to calculate both MCRT and then SRT.

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Mean Cell Resident Time (MCRT)

- **MCRT (example)**

3000 mg/L MLSS x 8.34 x (0.75 MG + 0.25 MG) =
25,020 pound of solids in Aeration and Clarifier(s)

7000 mg/L WSSS x 8.34 x 0.04 MGD =
2,335 ppd wasted

1 MGD Effluent Flow x 8.34 x 5 mg/L TSS =
41.7 ppd over weir

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Mean Cell Resident Time (MCRT)

- **MCRT (example)**
  - (MCRT) Mean Cell Resident Time

25,020 pound of solids in Aeration and Clarifier(s)

MLSS, lbs under aeration **+ solids in Clarifier**

lbs SS wasted + lbs SS lost in effluent

2,335 ppd wasted | 41.7 ppd over weir

2,377 ppd total waste | Calculate

= Days

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Solids Retention Time (SRT)

- **SRT (example)**

3000 mg/L MLSS x 8.34 x 0.75 MG =

18,765 MLSS lbs under aeration

7000 mg/L WSSS x 8.34 x 0.04 MGD =

2,335 ppd wasted

1 MGD Effluent Flow x 8.34 x 5 mg/L TSS =

41.7 ppd over weir

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Solids Retention Time (SRT)

- **SRT (example**
  - (SRT) Solids Retention Time

18,765 MLSS lbs under aeration

MLSS, lbs under aeration

lbs SS wasted + lbs SS lost in effluent

2,335 ppd Wasted | 41.7 ppd over weir

2,377 ppd total waste

= Days | Calculate

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$SRT^{(OXIC)}$

- **$SRT^{(OXIC)}$**
  - (SRT) Solids **Retention** Time =

MLSS, lbs OXIC Selector

lbs SS wasted + lbs SS lost in effluent

Industry Publications (WEF and others) are recommending the use of a $SRT^{(OXIC)}$ Formula to monitor and optimize the Nitrification Process (within BNR/ENR plants).

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$SRT^{(OXIC)}$

Higher targeted $SRT^{(OXIC)}$ values are necessary in the main Oxic Selector during fall and winter months when water temperatures are colder and the nitrification process slows down.

When pH drops in the Oxic Selector the nitrification process also suffers and a higher $SRT^{(OXIC)}$ value will be necessary.

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$SRT^{(OXIC)}$

- For BNR/ENR Processes an Oxic SRT allows for tighter control and the ability to determine an Operating SRT for nitrification.
- An Operating Oxic SRT in a BNR/ENR plant will vary with pH, Temperature, and D.O. and will also allow the comparison of Operating SRT to BOD:N ratio and other plant specific parameters.
-

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SRT$^{(OXIC)}$

- pH lower than 7.0 may require a longer Operating Oxic SRT
- Nitrification may require a longer Operating Oxic SRT when D. O. is less then 2.0 mg/L
- A longer Operating Aerobic SRT will typically be necessary during winter months.

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Process Performance Standards

- Secondary (or Final) Clarifiers
  - Detention Time in Hours
  - Weir Overflow Rate (WOR)
  - Surface Overflow Rate (SOR)
  - Solids Loading Rate (SLR)

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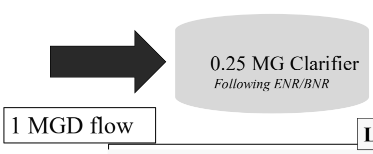
Detention Time (DT) for Clarifiers



Lets do the math

$$\frac{0.25\text{ MG} \times 24\text{ hours}}{1.00\text{ MGD}} = 6.0\text{ hours DT}$$

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Detention Time for Clarifiers

- Secondary (or Final) Clarifiers
  - DT used to be 2 to 4 hours
    - Today with BNR/ENR designs DT is 6 to 8 hours or more
    - Use forward flow only (disregard return flows)
    - Not as important w/ new clarifier designs
      - Other Parameters <u>now</u> dictate larger clarifiers
    - Common Process Control tool when more than one clarifier is available

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Detention Time for <u>Primary Clarifiers</u>

- On the other hand, the Detention Time of Primary Clarifiers should be monitored more closely.
- Especially in ENR Processes having several selectors (Anaerobic, Anoxic, and Oxic) that consume BOD.

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Detention Time for <u>Primary Clarifiers</u>

- Excessive Primary Clarifier DT will result in more BOD ending up in the Primary Sludge.
- Keeping Primary Clarifier detention times around 2 hours is recommended for ENR plants to help reduce the amount of a clean carbon that will need to be added.

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Weir Overflow Rate (WOR)

WOR, gpd/linear foot =

gallons per day
feet of weir length

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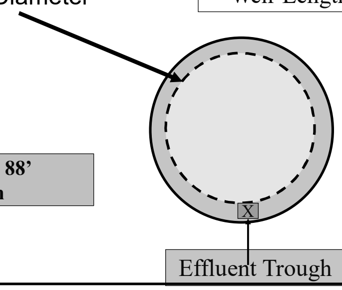
WOR, gpd/linear foot

- **Typical Secondary Clarifier**
  - 28 foot Weir Diameter

First Step
Calculate
Weir Length

28' dia x 3.14 = 88'
Weir Length



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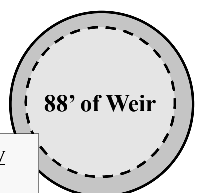
WOR, gpd/linear foot

- **Typical Secondary Clarifier**
  - 28 foot weir diameter

28' dia x 3.14 = 88'
Weir Length

0.50 MGD



500,000 gallons per day
88' of Weir

WOR = 5,682 gpd/lf

Let's do the math

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Weir Overflow Rate (WOR)

- Weir Overflow Rate (WOR),
  - Gallons per day divided by weir length **(gpd/ft.)**
  - Use forward flow only
  - 30,000 gpd/ft. **(Peak Hourly Flow)**
  - More critical for smaller plants
    - Package plants < 10,000 gpd/lf

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Surface Overflow Rate (SOR)

SOR, gpd/square foot =

gallons per day
clarifier, square footage

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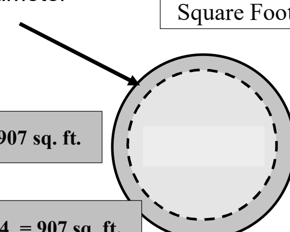
SOR, gpd/square foot

- **Typical Secondary Clarifier**
  - 34 foot Inside Diameter

First Step
Calculate
Square Footage



34' dia x 34' dia x 0.785 = 907 sq. ft.

OR

17' radius x 17' radius x 3.14 = 907 sq. ft.

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SOR, gpd/square foot

- **Typical Secondary Clarifier**

$$\frac{500{,}000 \text{ gallons per day}}{907 \text{ sq. ft.}} = 551 \text{ gpd/sq. ft.}$$

Lets do the math

0.50 MGD

500,000 gpd

907 sq. ft.

Compare to Design or Performance Standards

SOR = 551 gpd/sq. ft.

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SOR, gpd/square foot

- Secondary (or Final) Clarifiers
  - Surface Overflow Rate (SOR)
    - Gallons per day divided by surface area **(gpd/sq. ft.)**
    - Use forward flow only
    - Use Peak Hourly Flows

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SOR, gpd/square foot

- Surface Overflow Rate (SOR)
  - Clarifiers following Conventional Activated Sludge basins
    - 1,200 gpd/ Sq. Ft.
  - Clarifiers following Nitrification or Extended Aeration Basins
    - 1,000 gpd/ Sq. Ft. **At Peak Hourly Flows**

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Solids Loading Rate (SLR)

SLR = ppd/square foot

$$\frac{\text{pounds per day}}{\text{clarifier, square footage}}$$

$$\frac{\text{MLSS, mg/L} \times 8.34 \times (\mathbf{Q} + \mathbf{R})}{\text{Clarifier Square Footage}}$$

Q stands for Forward Flow

R stands for Return Flow

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Secondary (or Final) Clarifiers

- Solids Loading Rate (SLR)
  - Pounds of solids per day divided by surface area **(ppd/sq.ft.)**
  - Use forward flow and return flows along with mixed liquor concentration to calculate pounds
  - Calculate using "Peak Hourly Flow" for both Q and R

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SLR, ppd/square foot

- **Typical Secondary Clarifier**
- **3500 mg/L MLSS** **Use Peak Hourly Flow**
- **1 MGD Forward Flow (Q)**
- **0.8 MGD RAS Flow (R)**

907 sq. ft.

Let's do the math

$$\frac{\text{MLSS mg/L} * \text{Q+R Flow, MGD} * 8.34}{\text{Square Footage}}$$

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SLR, ppd/square foot

- Typical Secondary Clarifier
- 3500 mg/L MLSS
- 1 MGD Forward Flow (Q)
- 0.8 MGD RAS Flow (R)

Use Peak Hourly Flow

907 sq. ft.

Let's do the math

$$\frac{3500 \text{ mg/L} * 1.8 \text{ MGD} * 8.34}{907 \text{ Square Feet}}$$

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SLR, ppd/square foot

- Typical Secondary Clarifier
- 3500 mg/L MLSS
- 1 MGD Forward Flow (Q)
- 0.8 MGD RAS Flow (R)

Use Peak Hourly Flow

907 sq. ft.

What is your Answer?

= ppd/square foot

Is this a good SLR?

Process and Performance Standards

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Solids Loading Rate (SLR)

Clarifiers following Conventional Activated Sludge basins

50 ppd/ Sq. Ft. (Peak Hourly Flow)

Clarifiers following Nitrification, Extended Aeration Basins, or (BNR/ENR)

35 ppd/ Sq. Ft. (at Peak Flows)

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Process Performance Standards

- **Where to find**
  - 10 States Standards
    - MDE 2021 Wastewater Design Guidelines
  - Commonly accepted Standards
    - Water Environmental Federation MOPs
    - Engineering References
    - Sacramento Manuals
    - EPA Manuals

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Conventional Activated Sludge Processes

- **Conventional Activated Sludge**
  - **Common Modifications**
    - **Step Feed**
    - **Complete Mix**
  - **Sludge Re-aeration**
    - **Contact Stabilization**
    - **Kraus Process**

Why study these older Activated Sludge Processes and Modifications?

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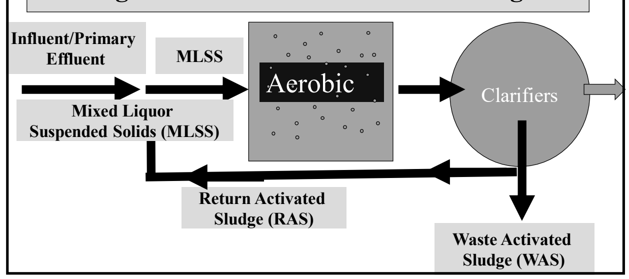
Widely Used in the 1950s through 1980's

The Conventional Activated Sludge Process

Designed for Effluent BOD 20 to 30 mg/L



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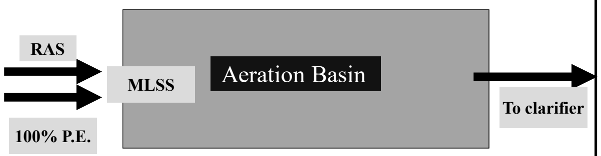
Typical Activated Sludge Feed Locations



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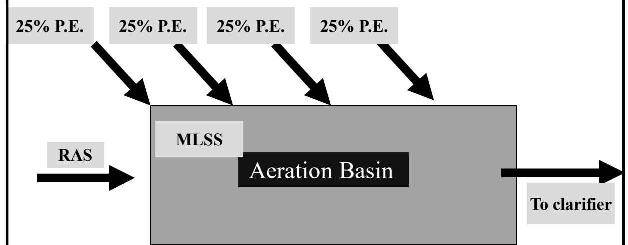
Step Feed



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Step Feed

Process Control Advantages

- Provides more control over F/M within basin
- Feeding P.E. at forward locations retains solids in aeration. Providing a lower SLR.
- Allows for a more evenly distributed oxygen environment

- Helps control bulky sludge
- Helps prevent rising sludge in clarifiers
- **Reducing solids loadings on clarifiers**

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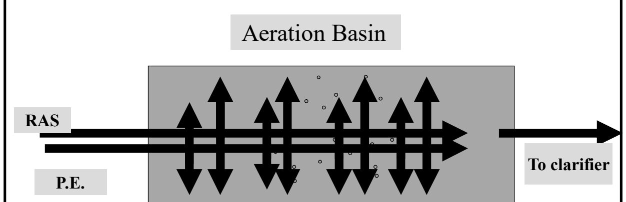
Complete Mix



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Complete Mix

Process Control Advantages

- Evenly distributes F/M Ratio within basin
- Helps control bulky sludge
- Helps prevent rising sludge in clarifiers

- Today, mixing technology is often used to achieve the advantages of Complete Mixing of Mixed Liquor, Primary Effluent, and Dissolved Oxygen.

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Step Feed and Complete Mix

Applications

- Operators can adopt to existing plants to address loading issues and deficiencies. Can also help with hydraulic and organic peak loadings.

- Often incorporated in advanced treatment technologies such as Sequencing Batch Reactors (SBR), Biological Nutrient Removal (BNR), and Enhances Nutrient Removal (ENR).

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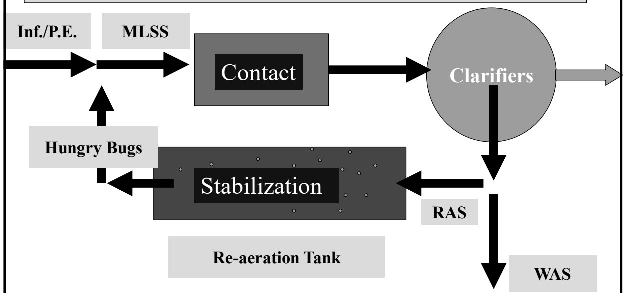
Widely Used in the 1960s through 1980's

Contact Stabilization

Designed for Effluent BOD 20 to 30 mg/L



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Contact Stabilization (Sludge Re-aeration)

Process Control Advantages

- Protection against solids wash out (clarifiers) as a result of high (peak) flows.
- Protection against toxic loads
  - Solids in the Stabilization basin are protected from short duration toxic loads
- BOD Uptake rate is high (bugs are hungry)
  - Can operate in a slightly higher F/M range

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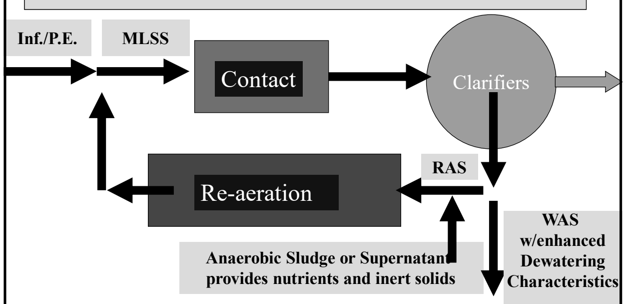
Kraus Process

Used for Nutrient Deficient Waste Streams



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Contact Stabilization and Kraus Process

Applications

- Unless modified, Contact Stabilization processes do not "Normally" nitrify very well (as with other Conventional processes).
  - Suitable for Pre-treatment of high organic wastewater.
  - High ammonia levels in the effluent

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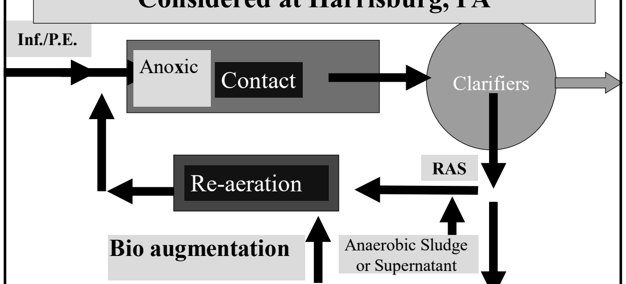
Sludge Re-aeration for Nitrogen Removal

Considered at Harrisburg, PA



Modification to a Sludge Re-Aeration (Kraus) Process

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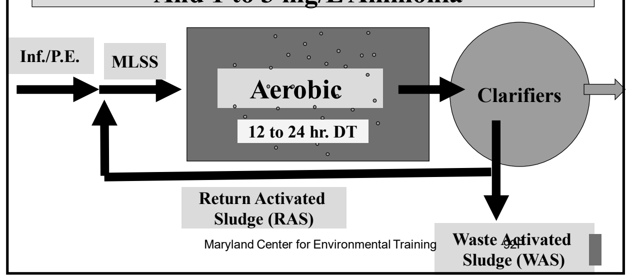
Extended Aeration and Nitrification Processes

Designed for Effluent BOD 10 to 30 mg/L And 1 to 3 mg/L Ammonia



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Extended Aeration and Nitrification Processes

Advantages and Applications

- Sized large enough for nitrification and additional BOD removal.
- Produces 20 to 30 percent less sludge than conventional systems.
- Often utilized in BNR and ENR upgrades.
- A lot operational reference material is available.

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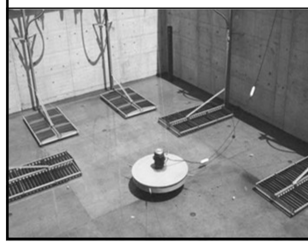
Sequencing Batch Reactors (SBR)

As the name implies, the SBR process is a sequencing batch treatment process. However not all of the processes referred to as SBR are both "sequencing" and "batch" in nature.



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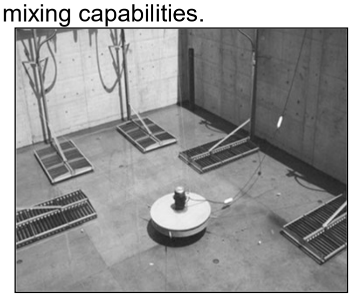
Sequencing Batch Reactors (SBR)

In a true SBR process each basin is filled with sewage and then flow to the basin is stopped before treatment is started. These basins are often square (or near square) and circular in shape to maximize the basin mixing capabilities.



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Sequencing Batch Reactors (SBR)

Other SBR basins are long and narrow to allow inflow to continue during treatment and (in some cases) even during the decanting process. Baffling is usually installed on the influent side and decanting takes place as far away from the incoming flow as possible.

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Sequencing Batch Reactors (SBR)

- Most treatment (except disinfection) performed in a single basin.
  - No clarifiers, No Return Sludge Piping
- Processes occur at a known time.
  - Fill (mixed and static)
  - React Fill
  - React (with and without aeration)
  - Settle
  - Decant (and idle)

How could these phases be used to achieve BNR? ???

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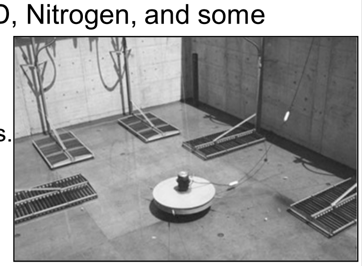
Sequencing Batch Reactors (SBR)

- PLC based controls
- If designed well for mixing, can be set up to remove BOD, Nitrogen, and some Phosphorus.
- Often good for Smaller systems.



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Activated Sludge Performance Standards

For Sequencing Batch Reactors

States are developing performance standards for Sequencing Batch Reactors. In most cases where SBR are utilized for domestic wastewater treatment the Nitrification or Extended Aeration Process Performance Standards will apply.

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SBR Operating Guidelines

- Basin Size
  - Total basin (reactor) size needs to be equal to 1.2 to 2.0 times the average daily flow.
- Basin depth
  - 10 to 20 feet with 1.5 to 2 feet of freeboard
- 2 or more basins are normally required
  - Dual basin systems are usually designed for short-term operations with only 1 basin in service

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SBR Operating Guidelines

- Number of cycles per day
  - 2 to 6 with 4 to 6 most frequently used
  - Longer cycle times better for nutrient removal
  - 4.5 cycles per day rotates dual basins on a daily basis
    - Tuesday 10 am basin 1 starts settle phase
    - Wednesday 10 am basin 2 starts settle phase

110

SBR Operating Guidelines

- Operating Parameters
  - Typically, Extended Aeration Range
    - F/M Ratio 0.05 to 0.10 lbs. BOD/day/lb. of MLVSS (some operators use MLSS)
    - Lower FM Ratios are common due to over sized basins
    - Sludge Age or SRT 15 to 45 days

111

SBR Operating Guidelines

- Operating Parameters
  - SBR are also used in high organic loading applications such as wastes from canneries and dairies.
    - F/M Ratio would be higher and Sludge Age or SRT would be shorter.

112

SBR Operating Guidelines

- Operating Parameters
  - To calculate F/M, SA, and SRT in SBR basins with varying aeration depths, pounds under aeration must be back-calculated to the Low Water Level which is usually the end of decant or decant stop level.
  - Provides a consistent starting point to evaluate day to day operations.

113

Stormwater Mode

As flows increase following a major rain event, the SBR basin will fill faster in the allotted time.

If a high level indicator or switch is activated early in a treatment phase the PLC controls will advance to Stormwater Mode of Operations.

At that time phases and cycle times are shortened until flows drop back to normal. Controls are usually in place to ensure that both basins will not discharge at the same time.

Operators should verify proper stormwater operations on a routine basis.

119

Biological Nutrient Removal (BNR) and Enhanced Nutrient Removal (ENR)

A brief introduction

120

What is considered Biological Nutrient Removal (BNR)

- Conventional Nutrient Uptake Rate is considered:
  - parts Total Nitrogen
  - part Total Phosphorus
  - Removed for every 100 Parts of BOD
- Any Biological Nutrient Uptake Rate greater than this would be considered BNR

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BNR and ENR Terms

- Selectors (by Definitions)
  - Aerobic or Oxic
    - Available D.O.
  - Anoxic (true)
    - Defined as 0 D.O. but with Nitrates
  - Anaerobic (true)
    - Defined as 0 D.O. and 0 Nitrates

123

BNR and ENR Terms

Aerobic, Anoxic, and Anaerobic <u>Selectors for flow-thru</u> processes are created by adding basins or compartments where aeration, mixing, and recycling flows options are utilized (or not utilized) to achieve desired results. The more flexibility an operator has in this area the better.

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BNR and ENR Terms

Aerobic, Anoxic, and Anaerobic <u>Selectors for SBR</u> processes are created by adjusting phase and cycle times and cycling air and mixing off and on to achieve desired results. Mixing is critical to optimize results.

125

BNR and ENR Terms

- **Aerobic (Oxic) Zone**
  - Typical aeration basins
    - 1.5 to 3.0 mg/L D.O.
  - 10-hour DT minimum
    - per MDE for ENR processes such as the 5 stage Bardenpho process

126

BNR and ENR Terms

- **Anoxic Zone**
- Mixing (no air)
  - Operators target 0.1 mg/L to 0.3 mg/L D.O.

True Anoxic Conditions is no Dissolved Oxygen. However, that is impractical to maintain under normal operations.

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BNR and ENR Terms

De-Nitrification?

- Anoxic Conditions
  - De-nitrification bacteria
  - Bacteria will consume the **Oxygen** in
    - NO_3-N and NO_2-N ← Primary Source of O_2
    - Nitrogen escapes as N_2 gas

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BNR and ENR Terms

The **Nitrification Process** consumes?

Oxygen
and Alkalinity

Key information for process control.

In the **De-nitrification Process**:

Two thirds of the oxygen consumed in the nitrification process is released during the de-nitrification process

and about ½ of the consumed alkalinity is also released.

129

BNR and ENR Terms

- **Anaerobic Zone (Bio-P Removal)**
  - Operators target < 0.1 mg/L D.O.
  - Operators target < 5 mg/L Nitrates

True Anaerobic Conditions is no Dissolved Oxygen and no available Nitrates. However, that is impractical to maintain under normal operations.

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BNR and ENR Terms

- **Anaerobic Zone or Selector**
  - **Selects or encourages the growth of bacteria that consumes BOD at a high rate and releases phosphorous while under anaerobic conditions.**
    - **Then under oxic (aerobic) or anoxic conditions will uptake phosphorous at an enhanced rate.**

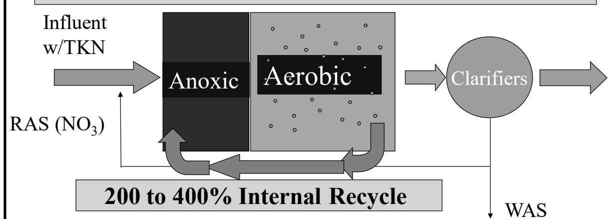
This is referred to as "Luxury Uptake of Phosphorus"
Possible Certification Exam Question

131

The MLE Process is the basic building block for most Activated Sludge BNR/ENR Processes.

De-nitrification Processes

Modified Ludzak Ettinger (MLE) Process
Effluent Total Nitrogen 5 to 8 mg/L



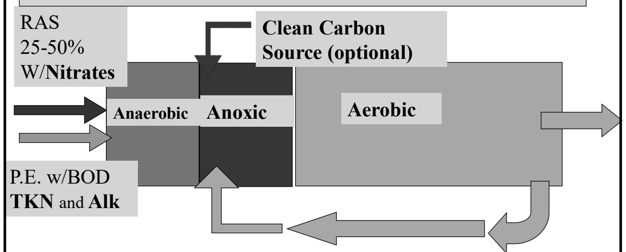
200 to 400% Internal Recycle

What is the purpose of Internal Mixed Liquor Recycle?

132

Bio-P and Improved Nitrogen Removal

Capable of Effluent
Total Nitrogen < 5 mg/L and Total P < 2 mg/L



Internal Recycle 200 to 400%

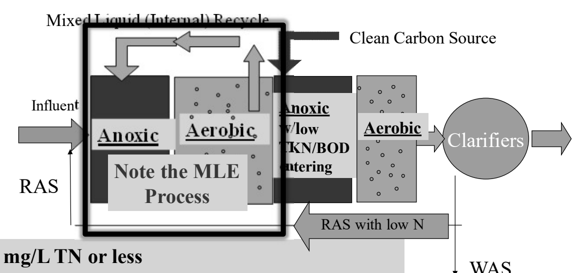
133

4 and 5 Stage Bardenpho Processes

Many of today's (flow-through) BNR/ENR Processes are off shoots or variations of Bardenpho Technology.

135

Enhanced Nitrification, and De-nitrification
Four Stage Bardenpho Process



3 mg/L TN or less
EPA mid-level Nutrient Removal Technology

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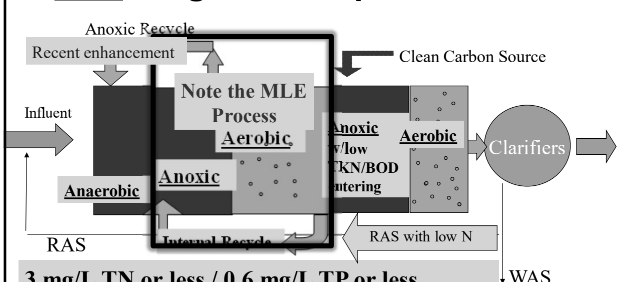
Enhanced Nitrification, and De-nitrification
Five Stage Bardenpho Process



3 mg/L TN or less / 0.6 mg/L TP or less

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Enhanced Biological Removal (ENR)

- Nitrogen Removal w/ 2 sets of anoxic/aerobic basins (such as the five - stage Bardenpho Process)
- Bio-P Removal
  - Followed by filtration
- Defined typically as
  - Removal down to less than 3 mg/L Total Nitrogen
  - And less than 0.3 mg/L Total P.
  - EPA is referring to it as Level 2 Nitrogen Removal Treatment Technology

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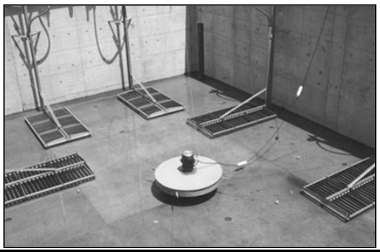
SBR and BNR Performance

- Many SBRs have adapted well to BNR operations. Specifically, well with denitrification.



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SBR and BNR Performance

- The use of ORP has been very effective for Nitrogen Removal in SBRs.
- Denitrification ORP Range
  - \- 100 mV to + 100 mV
- Nitrification ORP Range
  - \+ 125 mV to + 350 mV
  - ORP range for Nitrification may vary slightly depending on process and operational goals

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SBR and BNR Performance

- According to recent publications, the SBR phases namely **anoxic, anaerobic and aerobic** in single tank reactor design of **SBRs showed** effective biological nutrient removal (BNR) > 90%.

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SBR and BNR Performance

- Most SBRs can do a limited amount of Biological Phosphorus Removal. By utilizing ORP controls.
- Bio-P ORP Range
  - Extend Air-off cycle to drop ORP to - 200 mV
  - Take care to avoid septic conditions.

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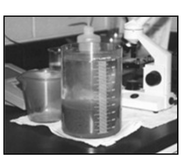
Process Control for Smaller Plants

- Settling Test and Sludge Volume Index (SVI)
- Micro exam - indicators and filamentous
- Mixed Liquor Suspended Solids (MLSS)
  - \- often uses centrifuge test to estimate
- FM ratio and a lesser degree Sludge Age (SA)



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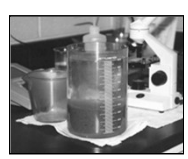
Process Control Larger Plants

- Settling Test and Sludge Volume Index (SVI)
- Micro exam - indicators and filamentous
- Mixed Liquor Suspended Solids (MLSS)
- Mixed Liquor Volatile Suspended Solids (MVLSS)
- FM ratio and SRT/MCRT

Why would smaller plants prefer not to use SRT/MCRT



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Before Changing Operations

Look for 2 or 3 additional witnesses:

- pH
- Alkalinity?
- D.O.
- FM
- GSA and/or SRT/MCRT
- Micro Life
- Settleometer (fast/slow/clarity/floc)

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Slow Settling Sludge

- Often caused by Young Age
- Very old sludge or too many solids
- Most often caused by filamentous bacteria.
- Very young sludge can settle very fast but with poor clarity.
- 600dpi-75.jpg 600dpi-76.jpg 600dpi-78.jpg 600dpi-79.jpg

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When Flows and Loadings Fluctuate Daily, Weekly, or Seasonally

Balance Out Loadings

- Add dog food! 1 to 2# dry dog food for each 1,000 gallons of influent lost on weekends or holidays.

-Add alkalinity

-Add nutrients

Dry dog food works well for small plants. Most brands will float making it somewhat time released.

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Common Process Problems

Slow Settling

- Check pH, alkalinity, D.O., FM, SA, Micro Life
- Excessive air or signs of G&O?
- Control/reduce Filamentous bacteria
  - By shutting off air or cycling air on and off
  - Chlorine aeration basin at 3 to 10 # Cl_2 per 1000 # MLVSS

However today most operators with start out with less than 3 # Cl2 / 1000 # MLVSS to be safe

152

Internal Mixed Liquor Recycle?

- Why recycle Nitrates back to Anoxic Zone
- D.O. in recycle must be kept low (<1.0 mg/L) if possible

153

Why an add a Carbon Source?

Carbon Source

- Is necessary when upstream processes depletes most of the available (organic) carbon
- Anaerobic and Anoxic Zones in addition to Aerobic Zones all require an organic carbon source
- **Methanol and Micro-C**

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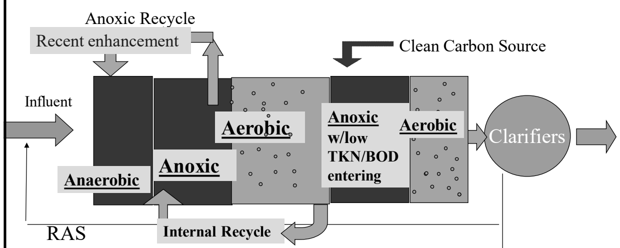
Enhanced Nitrification, and De

Now let's look at Selector Detention Times

Five Stage Bardenpho Process



3 mg/L TN or less / 0.6 mg/L TP or less

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Typical Setup for < 3 mg/L TN

- Anaerobic Selector (1.5 hours)
  - For Bio-P _HO3 Typical BNR Selector Setup
- Anoxic Selector (3.0 hours)
  - Internal Recycle (200 to 400%)
- Aerobic Selector (10 to 15 hours
- 2nd Anoxic Selector 1.5 to 2.0 hours
  - Clean carbon source
- 2nd Aerobic Selector (30 minutes)

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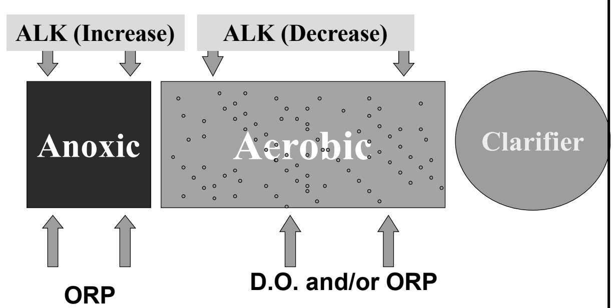
Monitoring Nitrification and Denitrification Processes



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BNR Rules of Thumb

- De-nit. falls off < 10 degrees C
- SBOD:SP at least 10 **or** 15**: 1**
  - for Bio-P **Add carbon if low**
- TBOD:TKN 5 **or** 10**: 1** **Add carbon if low**
  - lower --- more ammonia in effluent
- < 1 mg/L Nitrates leaving Anoxic (final) Zone
  - Adjust recycle rate, carbon source, and zone size to achieve

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BNR and ENR Terms

Forms of Nitrogen

- Total Nitrogen (TN)
  - Total Kjeldahl Nitrogen (**TKN**)
  - Nitrites (NO_2-N)
  - Nitrates (NO_3-N)
- **TKN** = Ammonia (60%) + *Organic N (40%)

Guideline only, ratio may or may not be constant

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BNR and ENR Terms

Forms of Phosphorus

- Total Phosphorus (difficult/expensive test)
  - Soluble/Insoluble **Soluble**
- Orthophosphate (PO_4^{3-})
  - (Soluble) Reactive Phosphorus
  - Test kits (may not be EPA approved)
  - (PO_4^{3-}) / 3.07 = P (soluble)
    - Some Test kits will read out as P (soluble)

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Process Control for Wastewater Operators

"Understanding the Process"



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MCET Instructor
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PART 2
Process Control Worksheets

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Outline for Part 2

- Pounds Formula
- Square/Rectangular Tanks – area & vol. Circular Tanks – circumference, area & vol.
- Calculate Pounds Under Aeration
- Understanding Flows
- Detention Time (DT)
- Weir Overflow Rate (WOR)
- Surface Overflow Rates (SOR)
- Solids Loading Rate (SLR)

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Outline for Part 2

- Solids Loading Rate (SLR)
- Organic Loading Flow-Thru Aeration Basins
- Sludge Age, SVI, and SRT
- Process Control Parameters for SBRs
- Back-Calculating MLSS Pounds to "Low Operating Level"
- F/M Ratio and Sludge Age for SBRs
- Sludge Volume Index (SVI) for SBRs
- Solids Retention Time (SRTO for SBRs
- Workgroup Problems No. 7 and No. 8

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Pounds Formula

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Pounds Formula

Pounds/day (ppd)

- ppd = mg/L x 8.34 x MGD
- mg/L = ppd / (MGD x 8.34)
- MGD = ppd / (mg/L x 8.34)

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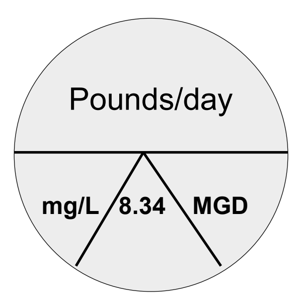
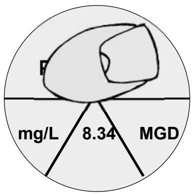
Pounds Formula



172

Pounds Formula

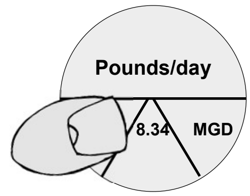
ppd = mg/L x 8.34 x MGD



173

Pounds Formula

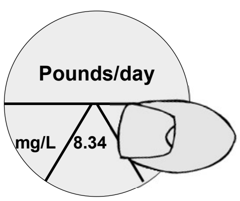
mg/L = $\frac{\text{Pounds per Day}}{8.34 \times \text{MGD}}$



174

Pounds Formula

MGD = $\frac{\text{Pounds per Day}}{\text{mg/L} \times 8.34}$



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Basic Formulas – Rectangular Tanks

- Area of a square or rectangular tank (sq. ft.)
  Length x Width (surface area)
- Volume of square or rectangular tank (cu. ft.)
  Length x Width x Depth
  to convert to gallons multiply by 7.48 gals per cu. ft.

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Basic Formulas – Circular Tanks

- Circumference of a circular tank (feet)
  3.14 x Diameter
- Surface Area of a circular tank (sq. ft.)
  0.785 x Diameter x Diameter
- Volume of a circular (cu. ft.)
  ***0.785** x Diameter x Diameter x Depth
  to convert to gallons multiply by 7.48 gals per cu. ft.

****0.785 is ¼ pi (3.14)***

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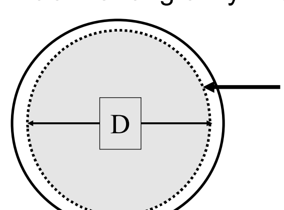
Circumference

- **Calculating Weir Length** – Circular clarifier or gravity thickener



Note the Difference:
Weir Circumference
Tank Circumference

Weir Circumference = **D** x 3.14

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Calculate Pounds Under Aeration

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Example #1 Calculate Pounds Under Aeration for a Rectangular Extended Aeration Basin

Tank Dimensions:
60 ft. long by 20 ft. wide and 12.0 ft. deep
Mixed Liquor Suspended Solids (MLSS):
3200 mg/L
% Mixed Liquor Volatile Suspended Solids (MLVSS)
85%

Example 1 Demo.xls

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Example #2 Calculate Pounds Under Aeration for a Circular Aeration Basin

Tank Dimensions:
60 ft. diameter and 12.0 ft. deep (at sampling)
MLSS:
2,000 mg/L
% MLVSS:
78%

Example 2 Demo

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Process Control Parameters

- Understanding Flows and Detention Time
- Clarifier Loading Rates
  - Weir Overflow Rate (WOR)
  - Surface Overflow Rate (SOR)
  - Solids Loading Rate (SLR)
- Organic Loading Rate (OLR) and F/M Ratio
- Worksheet example
  - #5 Flow-Thru OLR and F/M Ratio

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Understanding Flows

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Flow Rates

What do the following have in common?

1 MGD
694 gpm
1,000,000 gpd

They all represent the same Flow Rate

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Average Daily Flow (ADF) vs. Peak Flow Rates

ADF is the total flow and the average flow rate for a given day or on a monthly or annual basis.

Peak Flow is the highest sustained (or hourly) flow.

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Average Daily Flow (ADF) vs. Peak Flow Rates

Peak Factors are typically 2.5 to 4.0 times ADF. MDE Design Requirements

MDE requires for new plants to use the follow Peaking Factors:

- 0.0 to 0.25 MGD design plants use 4 x Design Capacity
- 0.25 to 16 MGD design plants use 2.67 x Design Capacity
- Over 16 MGD design plants use 2 x Design Capacity

Question to think about.
Why larger Plants have lower Peaking Factors?

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Q+R Flows

<u>Flows for Calculations</u>

For most PC formulas only forward flow is used.

A few will use both forward and return or recycle flows

<u>Q</u> means forward flow

<u>R</u> means return/recycle flows

<u>QR</u> or <u>Q + R</u> means both

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Detention Time (DT)

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Detention Time (DT)

<u>Detention Time, hours</u>

DT, hrs = <u>capacity x 24 hours</u>
Flow (Q)

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Detention Time (DT)

- **<u>Detention Time (DT) Hours</u>**

<u>Example:</u>

DT, hours = <u>25,000 gal. x 24 hours</u>
288,000 gpd

Let's Calculate

<u>Answer:</u> hours

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Clarifier Loading Rates

Weir Overflow Rate (WOR), **gpd/ft**

Surface Overflow Rate (SOR), **gpd/ft²**

Solids Loading Rate (SLR), **ppd/ ft²**

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Weir Overflow Rate (WOR) gpd/ft

Use Peak Hourly Flows

WOR becomes critical with smaller WWTPs

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Weir Overflow Rate (WOR)

Weir Overflow Rate (WOR), gpd/ft.

Gallons per Day (Q)
Feet of Weir Length

Example:
450,000 gpd
210 ft of Weir

Let's Calculate

Result: gpd/ft

Let's check
Process Performance Standards

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Surface Overflow Rates (SOR) gpd/ft²

Use Peak Hourly Flows

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Surface Overflow Rate (SOR)

Surface Overflow Rate (SOR), gpd/ft²

Example:
Flow, gpd
Surface Area, ft²

Note how units can help you do your math.

gpd/ft2

Notes:
Surface Overflow Rate – (Q) flow only

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Surface Overflow Rate (SOR)

Surface Overflow Rate (SOR), gpd/sq. ft.

Gallons per Day (Q)
Surface Area of Clarifier

Let's Calculate

Example:
4,800,000 gpd
6,000 sq. ft.

Is this within range for a clarifier?

Result: gpd/sq. ft.

Let's check
Process Performance Standards

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Example #4 Secondary Clarifiers Surface Overflow Rate (SOR)

Average Flow to Clarifier No. 1:
750,000 gpd
Peak Flow Rate:
2,000,000 gpd
Circular Clarifier:
45 ft. tank diameter

Example 4.xls

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Solids Loading Rate (SLR) ppd/ft^2

Use Peak Hourly Flows

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Solids Loading Rate (SLR)

Solids Loading Rate, ppd/ft^2

Example: Let's Calculate

45,036 ppd = ppd/ft^2
5,024, ft^2

Good or Poor SLR ?

Good SLR

Note:
Use both Forward (Q) and Return (R) Flows
ppd = MLSS, mg/L x 8.34 x (Q + R), MGD

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Example #5 Secondary Clarifiers Solids Loading Rate (SLR)

Average Daily Flow to Clarifier No. 1:
0.750 MGD
Peak Flow Rate:
2.00 MGD
Clarifier Surface Area:
1,590 sq. ft.
RAS Rate 90%
MLSS 2800 mg/L

Let's complete the Worksheet and then tell me if it's a good SLR?

Good or Poor SLR for Peak Hourly Flow?

Example 5.xls

201

Organic Loading Flow-Thru Aeration Basins

2 ways of calculating Organic Loading

Organic Loading Rate

F/M Ratio

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Organic Loading Rate

Organic Loading Rate, ppd/1000 ft^3

BOD, pounds per day
Volume, 1000 ft^3

Let's Calculate

Example:
2,500 ppd
122.4 1000 ft^3

Is this within range?

Use average monthly flow

Result: ppd/1000 ft^3

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Organic Loading Rate

Organic Loading Rate, ppd/1000 ft^3

- Daily and Monthly Average ppd BOD are used
- If PPD BOD peaks exceed 4 times the Daily Average
  - Continue to Monitor Peak BOD Loadings
  - Make operational changes as necessary

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Food to Microorganism (F/M) Ratio

Typically calculated as soon as BOD results are available from the lab.

6 or 7 days after sample was taken.

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Food to Microorganism (F/M) Ratio

- **FM Ratio** (based on MLVSS)

  ppd of BOD entering aeration

  pounds of MLVSS under aeration

Example:

Let's Calculate

16,680 # BOD
312,750 # under air
=

What mode of operation?

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Example #6 Flow-Thru Activated Sludge
Organic Loading Rate and F/M Ratio

Average Daily Flow to Basin No. 1:
0.800 MGD
Influent BOD:
160 mg/L
Basin Capacity:
0.500 MG
MLSS/MLVSS:
2200 mg/L / 1850 mg/L
Desired F/M Ratio:
0.10

Would you recommend Operational Changes?

Example 6 Demo.xls

210

Sludge Age, SVI, and SRT

- Sludge Age
- Sludge Volume Index (SVI)
- Solids Retention Time (SRT)
- Worksheet examples
  - #7 Flow-Thru SA and SVI
  - #8 Flow-Thru SRT

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Sludge Age

- **Sludge Age**

  MLSS, lbs

  *TSS to aeration, ppd

Example:

312,750 # under air
18,348 ppd TSS
= days

Let's Calculate

*ppd of TSS in P.E. or Raw (not MLSS not RAS)

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Sludge Volume Index (SVI)

Typically run on a daily or shift basis.

Measurement of MLSS Settleability and Density.

213

Sludge Volume Index (SVI)

- **SVI, ml/gm**
  - (SVI) Sludge Volume Index

$$\frac{\text{30 min. Settling Solids Volume, ml/L} \times 1{,}000}{\text{MLSS, mg/L}}$$

Let's Calculate

Example:

$$\frac{400 \times 1{,}000}{2500 \text{ mg/L}} = \quad \text{SVI}$$

Is this normally a good SVI?

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Example #7 Flow-Thru Activated Sludge
Sludge Age (SA) & Sludge Volume Index (SVI)

Flow Rate to Basin No. 1:	0.800 MGD
Influent TSS:	160 mg/L
Basin Capacity:	0.500 MG
MLSS/MLVSS:	2200/1850 mg/L
30 min. settling test	300 ml/L
Desired SA	10 days
Desired SVI	100

Example 7 Demo.xls

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SRT and SRT(Oxic)

- **SRT**
  - (SRT) Solids Retention Time

$$\frac{\text{MLSS, lbs under aeration}}{\text{lbs SS wasted + lbs SS lost in effluent}}$$

- **SRT(OXIC) (for BNR/ENR Process)**
  - (SRT) Solids Retention Time

$$\frac{\text{MLSS, lbs Oxic Zone or Selector}}{\text{lbs SS wasted + lbs SS lost in effluent}}$$

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Example #8 Flow-Thru Activated Sludge Solids Retention Time (SRT)

Effluent Flow (for Basin #1):	0.800 MGD
Effluent TSS:	5 mg/L
Basin Capacity:	0.500 MG
MLSS:	2200 mg/L
Waste Sludge:	11 gpm
Waste Sludge Suspended Solids (WSSS):	6,500 mg/L
Desired SRT:	11.0 Days\

..\Example 8 Demo.xls

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Process Control Parameters for Sequencing Batch Reactors

- Back-Calculating MLSS Pounds to "Low Operating Level"
- F/M Ratio and Sludge Age for SBRs
- Sludge Volume Index (SVI)
- Solids Retention Time (SRT)

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Process Control Parameters for Sequencing Batch Reactors

- Worksheet examples
  - #9 SBR – Calculating Pounds
  - #11 SBR – F/M Ratio, SA, and SVI
  - _ #12 SBR – Solids Retention Time (SRT)

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F/M Ratio and Sludge Age for Sequencing Batch Reactors

First Step

Back-Calculating MLSS Pounds to "Low Operating Level"

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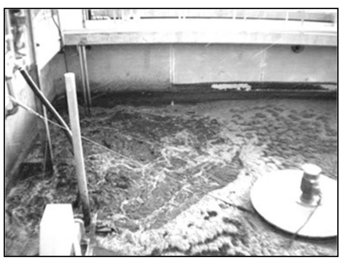
Using F/M Ratio and SA for Sequencing Batch Reactors

- Measure depth of basin at time of sample
- Then Convert to #MLSS or #MLVSS at "Low Water Level"



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Using F/M Ratio and SA for Sequencing Batch Reactors

An SBR that operate at variable depths throughout the treatment process, will normally return to the same "Low Water Level" at sometime within each cycle. This is usually the depth of the basin immediately following the Decant Phase.

Back calculating pounds under aeration to the "Low Water Level" allows for a constant F/M and SA.

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Back-Calculating MLSS pounds to "Low Operating Level"

- MLSS at sampled Depth = 2000 mg/L
- Sample Depth = 12.0 feet
- Low Water Level (LWL) Depth = 9.5 feet
- Conversion factor (CF) = 12.0/9.5 = 1.263
- 2000 mg/L x 1.263 = 2526 mg/L
- 2526 mg/L is the "Low Operating Level" MLSS
- Use 2526 mg/L and the capacity of the basin at "Low Water Level" for determining pounds of MLSS or MLVSS. Then use as you normally would for SRT, FM, and Sludge Age calculations.

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Example #9 Sequencing Batch Reactor Calculating Pounds Under Aeration (Square or Rectangular Basins)

Dimensions:
90 feet long by 80 feet wide
9.5 feet LWL
MLSS/MLVSS:
2500 mg/L / 1850 mg/L
Depth of Basin at Sampling:
14.5'

Calculate for Basin No. 1

Example 9 Demo.xls

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Example # 11 Sequencing Batch Reactor Food To Microorganisms (F/M), Sludge Age (SA), and SVI

Flow to Basin No. 1:
 0.750 MGD
Influent BOD:
 180 mg/L
Influent TSS:
 170 mg/L
Settling Test:
 480 ml/L at 60 minutes
MLSS: 2,500 mg/L
Pounds of MLSS/MLVSS at LWL:
 16,282 / 12,049 as calculated in Example #9

Example 11 Demo.xls

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Example #12 Sequencing Batch Reactor Solids Retention Time (SRT)

Effluent Flow (Basin #1):	0.750 MGD
Effluent TSS:	6 mg/L
MLSS at LWL:	16,282 pounds
Waste Sludge (rate):	160 gpm
Wasting time:	24 mins./cycle
Cycles per day:	5
WSSS:	6,500 mg/L
Desired SRT:	14.0 Days

Example 12 Demo.xls

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Additional Worksheet Examples

#3 Detention Time (DT)
#10 SBR Pounds Under Aeration Circular Tank

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Example #3 Detention Time

Average Flow:
 504,000 gpd
Peaking Factor:
 3.0
Circular Clarifier:
 42 ft. diameter
 and 12.0 ft. average depth

Example 3.xls

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Example #10 Sequencing Batch Reactor Calculating Pounds Under Aeration (Circular Basins)

Dimensions:
 90 feet diameter
 9.5 feet LWL
MLSS/MLVSS:
 2500 mg/L / 1850 mg/L
Depth of Basin at Sampling:
 14.5’

Example 10.xls

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Workgroup Problems

- Workgroup Problem No. 7
- Workgroup Problem No. 8

- Start at 2:45 pm to complete both

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Workgroup Problem No. 7

Process Control for Flow-thru A. S. WWTP

- Nitrifying Activated Sludge WWTP Calculating F/M Ratio, Sludge Age, SRT, and SVI for Basin No. 2
  - Two basins are in service (Basins Nos. 1 and 2)
  - Worksheets Used: Use _HO6 Workgroup Problem No7
  - #6 Flow-Thru OLR and F/M Ratio for Workgroup Problem No. 7
  - #7 Flow-Thru SA and SVI for Workgroup Problem No. 7
  - #8 Flow-Thru SRT for Workgroup Problem No. 7

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Workgroup Problem No. 8

Process Control for Sequencing Batch Reactor (SBR)

- SBR F/M Ratio, Sludge Age, and SVI
- Two SBR basins are in service
- Calculate F/M Ratio, SA, and SVI for SBR Basin No. 2 Use _HO7 Workgroup Problem No8
- Worksheets Used:
  - #10 Calculate Pounds under aeration for Workgroup Problem No. 8
  - #11 Calculate F/M Ratio, SA, and SVI for Workgroup Problem No. 8

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Class Closeout

- Course Evaluation (Survey)
  - Link will be provided
- Post Test
  - Link will be provided
- Email Instructor at CGFarley@CSM.edu
- To obtain Excel files for all 12 Worksheets and for answers to Examples and Workgroup Problems.

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