# Activated Sludge - BOD

MCET

environmental, health, and safety training

# Wastewater Treatment
**Activated Sludge**
**BOD Removal & Nitrification**

Steve Elder

1

1

## Clean Water Act (CWA)

- The 1972 Clean Water Act:
  - Set the basic structure for regulating point source discharges of pollutants into US waterways
  - Gives EPA authority to set **water quality standards** for contaminants:
    - Attain water quality levels that make surface waters safe to fish and/or swim in
    - Restore and maintain the chemical, physical, and biological integrity of the nation's waterways

2

2

## Clean Water Act (CWA)

- The CWA makes it unlawful for any person to discharge any pollutant from a point source into navigable waters unless a NPDES discharge permit is obtained
- NPDES - National Pollutant Discharge Elimination System
- WWTPs are self-monitored
  - Monthly "Discharge Monitoring Reports" (DMRs)
- EPA has delegated monitoring responsibility to states

3

3

## Goals of Wastewater Treatment

- Removal of:
  - **Suspended solids and organic matter** (cBOD and nBOD) to limit pollution
  - **Nutrients** (TP and TN) to limit eutrophication
  - **Microbiological contamination** to eliminate infectious diseases
- Required levels of treatment are based on NPDES regulations as prescribed in issued discharge permits

4

4

## Wastewater Influent Characteristics

- Measurement and sampling at head works:
  - Flow metering continuously records the volume of water entering the treatment plant
  - Samples are taken for determination of:
    - TSS
    - BOD
    - TN
    - TP
    - pH and alkalinity

5

5

## Key Wastewater Constituents

- pH
  - An expression of the intensity of basic or acidic conditions, 0 (most acidic) to 14 (most basic); 7 neutral
  - Microorganisms most active 6.5 - 8.0
  - Nitrification is inhibited at pH 6.0 or less
- Alkalinity
  - Measure of wastewater ability to buffer pH change
  - Nitrification is inhibited at pH of 6.0 or less
- Pathogenic organisms
  - E-coli indicator
  - Numbers are limited in permit



6

6

## Key Wastewater Constituents

- BOD – Biochemical Oxygen Demand
  - Typically, a five-day test is used to determine the quantity of oxygen used by microorganisms.
  - The higher the BOD concentration, the greater the wastewater strength (organic matter or food).
  - Raw sewage concentrations - 150 to 300 mg/l
  - Valid five-day BOD testing conditions:
    - BOD incubator temperature - 20°C
    - DO uptake - 2.0 mg/l
    - DO remaining after five days -1.0 mg/l

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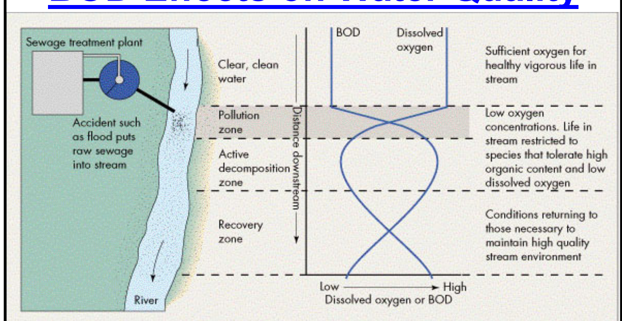
## BOD Effects on Water Quality




All streams have capacity to degrade organic waste; problems occur when stream is overloaded

8

8

## Key Wastewater Constituents

- TSS – Total Suspended Solids
  - Substances in wastewater that can be removed by physical means
  - Sedimentation and filtration unit processes are used to remove TSS from wastewater
  - Raw sewage concentrations -150 to 300 mg/l
  - Valid TSS testing conditions:
    - Temperature in a drying oven - 103°C
    - VSS burn off at 550°C

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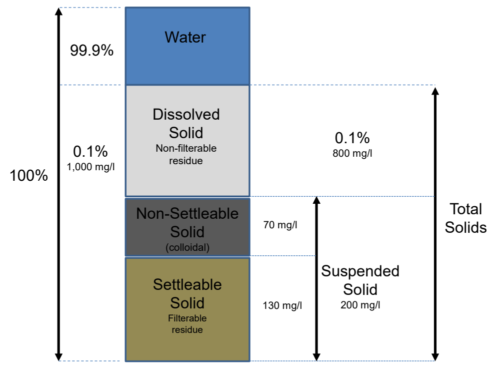
## Typical Wastewater Solids Composition

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10

Which of the following is the best lab test to measure solids in the aeration basin?

a. settleometer.

b. mixed liquor volatile suspended solids.

c. total dissolved solids.

d. total organic carbon.



11

## Key Wastewater Constituents

- Nutrients
  - TP – Total Phosphorus
  - TN – Total Nitrogen
- Phosphorus and Nitrogen compounds are nutrients that can stimulate algae production in receiving waters
- Typical concentrations:
  - TP – 3 to 5 mg/l
  - TN – 30 to 40 mg/l



12

## Secondary Treatment

- Influent contains high levels of organic material
  - Biological Oxygen Demand – (~150 mg/l)
  - Organic nitrogen – (~20 mg/l)
  - Organic phosphorus – (~2 mg/l)
- Three common biological treatment processes:
  - **Activated sludge**
  - Trickling filters
  - Stabilization ponds (Lagoons)

13

13

## Activated Sludge

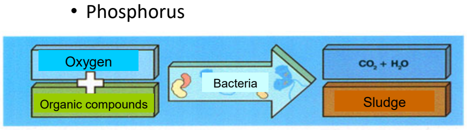
- **Secondary treatment** - the biological treatment of wastewater:
  - Activated sludge is a type of secondary treatment
  - Removes a high level of biodegradable organic pollutants (BOD) to protect receiving water quality that sedimentation alone can't provide
- **Activated Sludge** - a mixture of bacteria, fungi, protozoa (single cell), and metazoan (multi-cell) organisms maintained in suspension by aeration and mixing

14

14

## Activated Sludge

- Growth and retention of suspended biological sludge using oxygen to remove:
  - Soluble Organics (cBOD, COD)
  - Organic Solids (TSS, VSS)
  - Nutrients
    - Nitrogen
    - Phosphorus

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## Activated Sludge

- Oxidizes carbonaceous matter (BOD)
- Nitrifies ammonium-N to $NO_3$-N (MCRT > 10 days)
- MCRT:
  - > 1 day for BOD removal
  - > 5 days for nitrification (Temperature dependent)
- DO concentrations:
  - > 1.0 for BOD removal (Range: 1 – 2 mg/l)
  - > 2.0 for nitrification (Range: 2 – 5 mg/l)
- MLSS concentrations – 2000 to 8000 mg/l
  - MLVSS – should be 70 -80 % (minimum)
- RAS – 35 - 50% of influent flow

16

16

What DO level should be maintained in an activated sludge aeration tank?

a. 0 - 1 mg/L
b. 1 - 2 mg/L
c. 3 - 5 mg/L
d. 5 - 7 mg/L

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## Fundamentals

Microbiology

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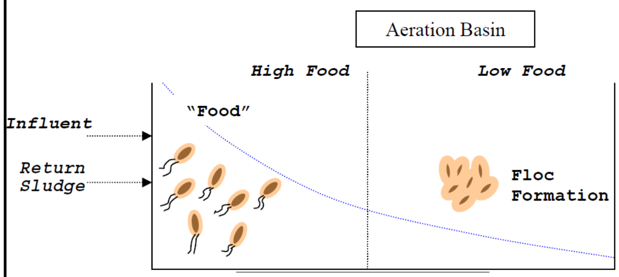


- When Food is plentiful bacteria swim around and do not form floc – turbid effluent
- When food is low they lose their cilia and begin to floc together

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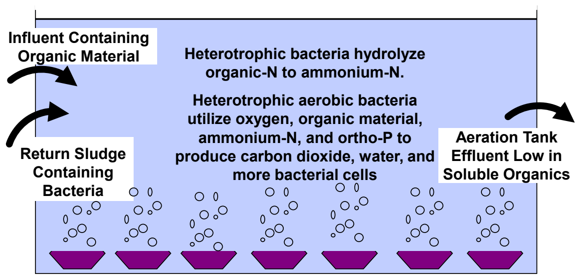
# BOD Removal in the AS Process

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# Microbiology of Activated Sludge Aerobic Processes

- Biological processes removing carbonaceous BOD under aerobic conditions employ heterotrophic bacteria for oxidation of organics
- Approximately 95% of biomass in activated sludge processes is heterotrophic bacteria
- They consume soluble organic matter
- Solid particles consumed in a two step process:
  - Adsorption – particles stick together, bacteria release enzymes that dissolve particles into small particles
  - Absorption - these small particles can pass through cell wall

 21

21

## Activated Sludge

- Protozoa (single-cell organisms)
  - Amoeba
  - Flagellates
  - Free-swimming ciliates
  - Stalked ciliates

❑ What do they do for us?
- Consume organic matter
- Consume bacteria
- Participate in floc formation

 22

22

## Activated Sludge

- Metazoans (multi-cell organisms)
  - Rotifers
  - Nematodes
  - Worms

❑ What do they do for us?
- Consume bacteria, algae, protozoa
- First to be impacted by a toxic load
- "Water Bears" indicate little or no ammonia present
- Older sludge

 23

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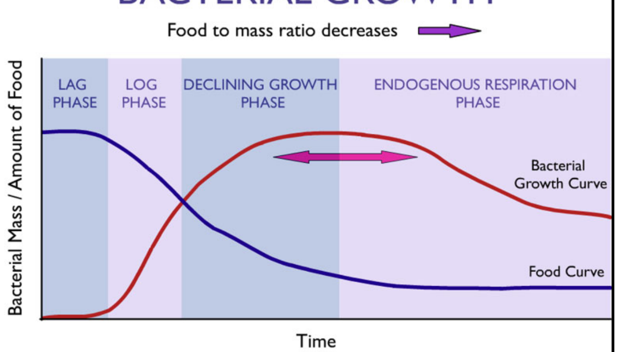
## BACTERIAL GROWTH

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## Bacterial Growth Curve

- LAG
  - Bacteria are present
    - Fecal waste
    - I/I
  - Bacteria enter an "adjustment" period
    - New environmental or operational conditions
    - New substrates
    - Development of enzyme systems

25

## Bacterial Growth Curve

- LOG
  - Consists of two phases
    - cBOD uptake, soluble cBOD only absorbed
      - Increase in volatile content
      - No increase in bacterial numbers
    - cBOD synthesis
      - cBOD converted to new bacterial cells (MLVSS)
      - Increase in bacterial numbers

26

## Bacterial Growth Curve

- Endogenous
  - Substrate at stationary or "steady-state"
  - Population "levels off" to "steady state"
  - Endogenous has declining curve
    - Periods of time when little or no food is present
    - Bacteria consume stored food
    - They start sticking together (floc)
- Endogenous, basal
    - Bacteria consumed cytoplasm
    - Death / little or no growth
    - Reduced volatile content in extended aeration
    - Number of bacteria is reduced

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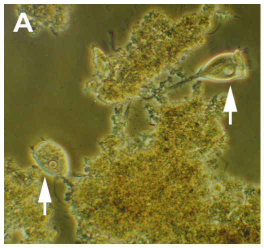
## Floc Biology - Indicator of AS Health

- The diversity and activity of organisms found in floc can indicate the health of the biological process.
- An abundance of protozoans such as rotifers indicates healthy situation

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28

## Microbial Ecology of Activated Sludge Aerobic Processes

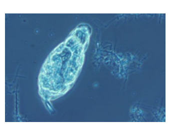
- Biological processes removing carbonaceous BOD under aerobic conditions employ chemoheterotrophic bacteria for oxidation of organics
- Approximately 95% of biomass in activated sludge processes is chemoheterotrophic bacteria

29

29

## Microbial ecology of aerobic processes

- Remaining 5% of biomass consists of protozoans and metazoans
  - Presence of protozoans and metazoans indicates toxic free influent
  - Ciliated protozoan indicate good settling sludge
  - Free swimming protozoan indicates dispersed growth (poor settling)
  - A small fraction of biomass is multi-cellular metazoans



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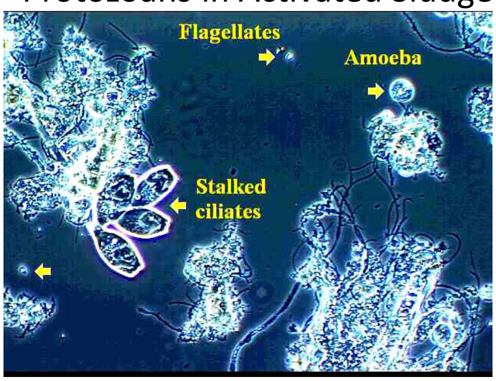
## Activated Sludge

- Protozoa (single-cell organisms)
  - Amoeba
  - Flagellates
  - Free-swimming ciliates
  - Stalked ciliates
- Metazoans (multi-cell organisms)
  - Rotifers
  - Nematodes
  - Worms
  - "Water Bears"

31

31

## Protozoans in Activated Sludge

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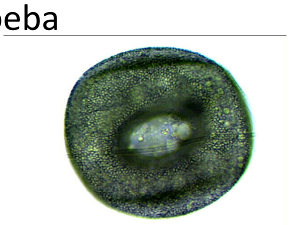
32

## Amoeba

- Single-celled protozoans
- Indicative of "young" sludge
- Minimal contribution in WW treatment
- High concentration =
  - BOD shock loading
  - Presence of large amount of particulate matter
  - Lack of DO



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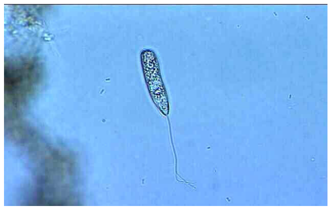
## Flagellate

- Nutrient uptake is by absorption
- Peak after amoebae
- Presence -> high soluble food concentration
- Presence indicates high amount of soluble organic nutrients



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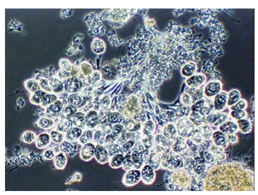
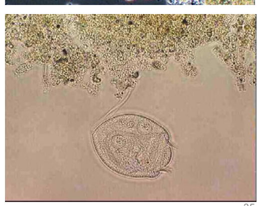
## Ciliates

- Free-swimming
  - Peak after flagellates/ correspond to peak in bacteria concentrations
- Stalked
  - Peak after free-swimming
  - Good indicator of settleable sludge
- Crawling
  - More dominate as food declines





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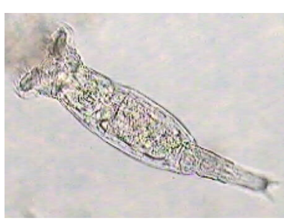
## Rotifers

- Number very small
- Appear late in development of activated sludge
- Indicative of "old" sludge
- Sensitive to $NH_3$ , pH, temperature

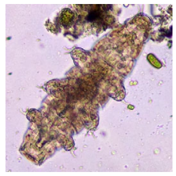


36

36

# "Water Bears"

- _Tardigrade_
- Eight legs
- Can't tolerate $NH_3$
- Presence in activated sludge biomass indicates absence of $NH_3$
- Feeds on other protozoa



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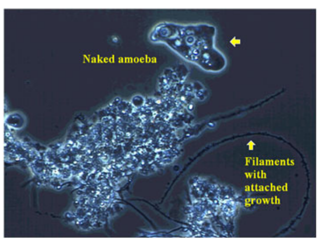
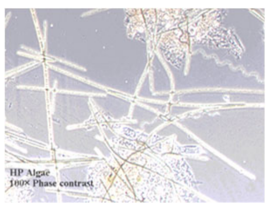
# Filaments

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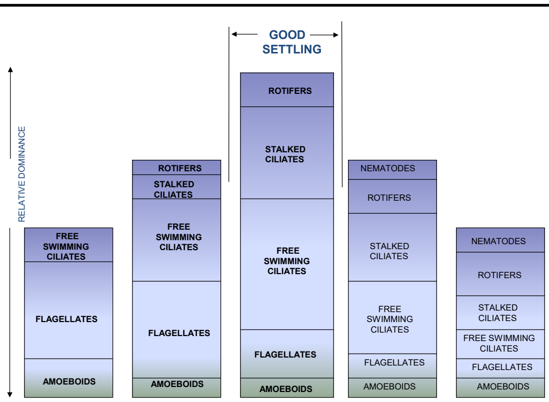



Relative Number of Microorganisms vs Sludge Quality

39

39

What combination of microorganisms would reflect a well balanced activated sludge?

a. flagellates, rotifers and nematodes.
b. amoeboids, ciliates and nematodes.
c. flagellates, ciliates and rotifers.
d. amoeboids, rotifers and nematodes.

40

40

What is the correct sequence of the microorganism growth phases?

a. endogenous, declining growth, logarithmic.
b. endogenous, logarithmic, declining growth.
c. logarithmic, endogenous, declining growth.
d. logarithmic, declining growth, endogenous.

41

41

# Activated Sludge

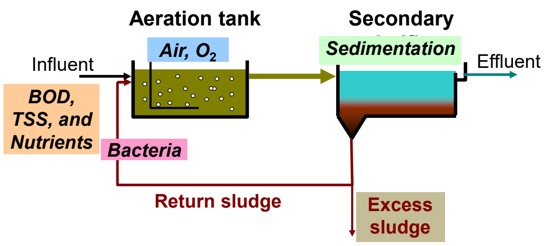
Overview of Processes

42

42

## Activated Sludge Process

- The most widely used wastewater treatment process in the USA








## Activated Sludge Processes

**What can activated sludge processes remove?**

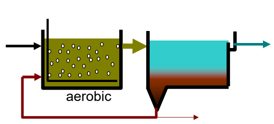
1. **cBOD:**
   - **Dissolved organic materials**
2. **nBOD - Convert ($NH_3$-N) to ($NO_3$-N)**
3. **Nutrients**
   - **Phosphorus**
   - **Nitrogen**
4. **Total suspended solids (TSS):**
   - **Suspended organic and inorganic particulate solids**



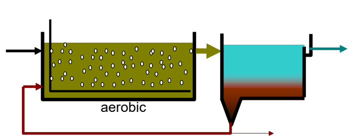


## Activated Sludge BOD & Nitrification

**cBOD Removal**




**Nitrification**



## Activated Sludge Steps

1. Mixing return sludge with wastewater forming a *mixed liquor*
2. *Aeration* and agitation of the mixed liquor (biomass) for a period of time
3. Separation of activated sludge from the mixed liquor in a *sedimentation* process
4. *Return* of the proper amount of activated sludge for mixture with wastewater
5. *Wasting* of excess activated sludge

46

46

## Basic Process Components

- Aeration Tank (Reactor)
  - Mixed liquor
  - Mixed liquor suspended solids (MLSS) - Biomass
  - Aeration (and mixing) system
- Secondary clarifier
  - Return activated sludge (RAS)
  - Waste activated sludge (WAS)

47

47

## Aeration

- The purpose of aeration:
  - To dissolve oxygen into wastewater so that activated sludge microorganisms can utilize it while they break down organic material
- Aeration is also used for mixing purposes and to enhance biological growth

48

48

Where should you take a sample in an aeration tank to measure solids settleability?

a. beginning.

b. middle.

c. end.

d. At the same location as the DO sensor so you can correlate the SVI.

49

49

## Various Activated Sludge Configurations

- Basin Type:
  - Complete Mix
  - Plug flow reactor
- Air and Feed Options
  - Tapered aeration
  - Step feed
  - Pure oxygen
- Oxidation ditch & Extended Aeration
- Sequencing batch reactor

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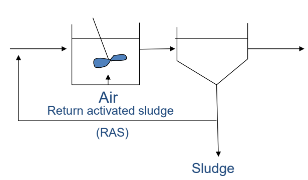
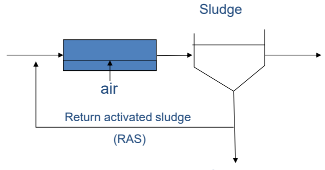
## Most Common Configurations




**Complete mix** activated sludge process




**Plug Flow process**

Conventional Activated Sludge

51

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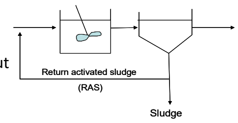
# Complete Mix Activated Sludge



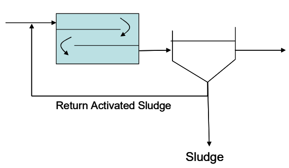

- Advantages:
  - Uniform MLTSS concentration throughout
  - dilutes shock loads
  - relatively simple to operate
- Disadvantages:
  - has low DO and low F/M that encourages growth of filamentous bacteria (sludge bulking!)
  - Less efficient – larger tanks – limited Solids in the reactor
  - May have problems with short circuiting

52

52

# Activated Sludge - Plug Flow

- Disadvantage
  - Biologically instable when flows vary
- Advantage
  - Avoids “bleed-through” / passage of untreated substrate
  - More efficient - smaller

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# Activated Sludge - Plug Flow

54

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## Conventional Activated Sludge

- Most common activated sludge process for secondary treatment (cBOD, nBOD, and TSS removal) is plug flow.
- **Plug-flow** basin designed for improved efficiency and small foot-print; tanks are in series
- **Tapered aeration** option to optimize dissolved oxygen supply to match demand in basin.

55

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## Conventional Activated Sludge

- **PLUG FLOW -** Long narrow tank, or a series of several long tanks
- Primary effluent and return activated sludge (RAS) combined at influent of aeration tank
- Dissolved oxygen (DO) demand is highest at the aeration tank entrance; more air (oxygen) is required
- As BOD is depleted, process may successfully operate in the nitrification mode.

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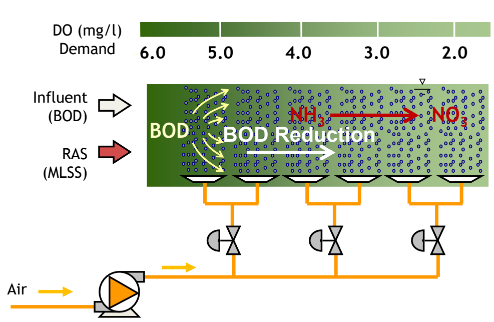
## Conventional Activated Sludge

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What effect would an overloading of BOD have on the biological growth in the aeration tank?

a. the oxygen uptake rate would increase.
b. the BOD removal efficiency would increase.
c. the F/M would decrease.
d. the pH would increase.

58

58

## Tapered Aeration

- Deliver more air at the entry points of the aeration tank where the dissolved oxygen demand is at it's highest
- Dissolved oxygen demand is less the exit of the process
- The attempt is to efficiently address oxygen uptake where needed

59

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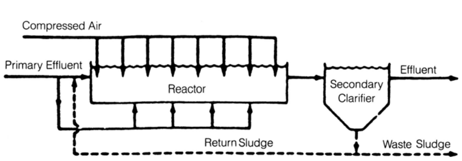
## Step Feed Activated Sludge

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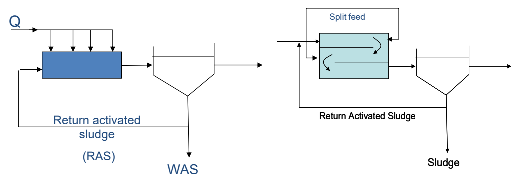
## Step Feed Activated Sludge

- Flow introduced at 3-4 points in aeration tank to equalize F/M
- High solids inventory – higher MCRT

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## Step Feed Activated Sludge

- Advantages of Step-Feed Configuration:
  – Equalize Food/Mass ratio across basin
  – 3 to 4 Passes and influent points
  – Reduces peak oxygen demand – energy efficiency
  – Flexibility to match operating conditions
  – Higher SRT and biomass inventory
  – Lower solids concentration at the end of the aeration tank, lowering the Solids Loading Rate on the final settling tanks

62

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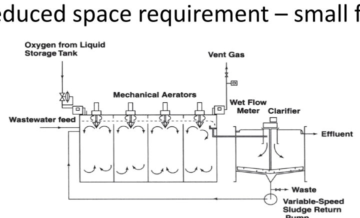
## Pure Oxygen Plug Flow

- Staged enclosed reactor
- $CO_2$ accumulation; lower pH; limits nitrification
- High purity oxygen generated on site
- Reduced space requirement – small footprint

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## Oxidation Ditch

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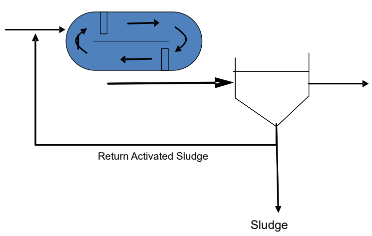
## Oxidation Ditch

- Unidirectional channel flow
- 0.2-0.3 m/s velocity keeps sludge in suspension
- Long HRT (24 hrs), long MCRT (>30 days)

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How does biological activity in an oxidation ditch react to the winter?

a. increases.
b. decreases.
c. no change.

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## Activated Sludge - Extended Aeration

- Stable with intermittent loads
- Long aeration time > 24 hours
- Low organic loadings:
  - 5 to 15 lbs/day/1000 $ft^3$ of aeration
  - Food-to-mass – 0.04 to 0.1
- Solids Residence Time – 20 to 40 days
- Remote facilities:
  - Schools, churches, and mobile home parks
  - Tourist and rest stop facilities

67

67

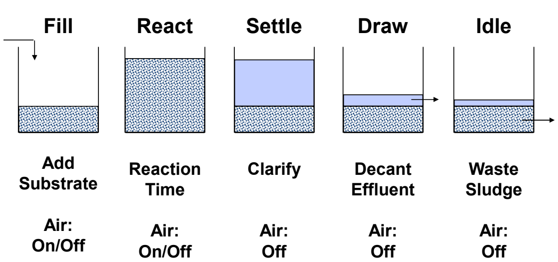
## Activated Sludge - Extended Aeration

- MLSS – Range from 2000 to 8000 mg/l.
- Due to the low food/high microbe ratio (F:M ratio), stored food in dead microorganisms is consumed (endogenous respiration)
- Sludge production is much less than other waste activated sludge processes

68

68

## Sequencing Batch Reactor




69

69

## Activated Sludge

Aeration

70

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## Aeration

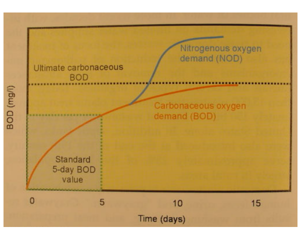
- Conventional activated sludge is an aerobic process. Many organisms in the activated sludge process need free oxygen ($O_2$) to convert food into energy for their growth.
- Dissolved Oxygen (DO) concentrations:
  - Less than 1 mg/l - bulking potential
  - BOD removal - normal 1 to 2 mg/L
  - "Nitrification" - 2 to 5 mg/l

71

71

## Oxygen Requirements

- Biological treatment:
  - cBOD removal – from organic matter and suspended solids
  - nBOD removal – Nitrification, convert ammonia nitrogen to nitrate nitrogen (before denitrification)

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## Why is Aeration Important?

- Dissolved oxygen is ***an essential*** substrate in activated sludge processes
- Oxygen is ***sparingly soluble*** in water; it may be the ***growth-limiting substrate***
- For activated sludge, the ***critical oxygen concentration*** is about 10% to 50% of dissolved oxygen saturation concentration

73

73

What should the operator do if the DO at the influent end of the aeration tank is 0.7 mg/L and at the effluent end it is 6.0 mg/L?

a. decrease the air at the influent end and increase the air at the effluent end.

b. increase the air at the effluent end only.

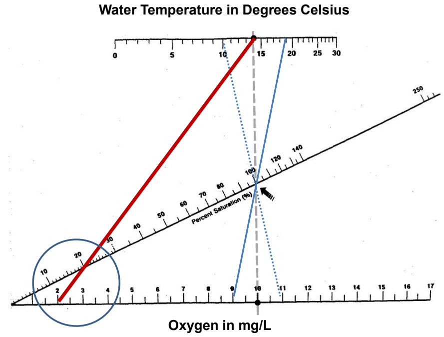
c. adjust the air flow so it is tapered from influent end to effluent end.

d. no adjustment is needed.

74

74

## D.O. - Percent Saturation in Water




Source: Department of Fisheries and Aquatic Sciences, University of Florida

75

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## Aerobic Processes

- Aerobic processes which requires $O_2$ for removal of organics (BOD) and nitrification
- Oxygen can be supplied by air or as pure $O_2$
- Oxygen can be delivered through mechanical (surface) or diffused aerators
- Aeration in activated sludge processes serve two purposes:
  - To satisfy oxygen needs
  - Mixing

76

76

## Mixing requirements

- Generally for air Activated Sludge systems, satisfying oxygen demand supplies enough mixing to keep biomass in suspension
- Mixing may be limiting for pure $O_2$ and extended aeration systems
- In these cases additional mixing (power) must be supplied

77

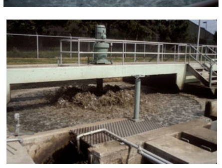
77

## Mechanical Aerators

Two basic types commonly used
Low speed surface aerators
Submerged turbine aerators

<u>Low speed surface aerators</u>
- Most common type in AS
- $O_2$ transfer rate low
- Dissipate heat quickly

<u>Submerged turbine aerators</u>
- Higher gas transfer efficiencies
- High energy requirements



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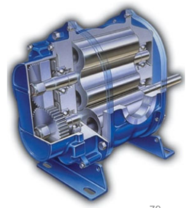
78

## Positive Displacement Blowers

- Typically rotary lobe type
- Long operational history
- Higher pressure / variable pressure
- Many manufacturers
- Lower efficiency
  - Slip around lobes
  - Additional power to overcome pressure drop across inlet/discharge silencers/filters
- Noisy
- Vibration can be high
- Good for variable pressures



Courtesy of Dresser-Roots

79

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## Multistage Centrifugal Blowers

- Multiple impellers in series increase air pressure
- Historically used at medium to large WWTPs
- Have good track record / reliable operation
- Primary manufacturer - Gardner-Denver
- Limited efficient turndown
  - Inlet throttling
- Can be noisy

80

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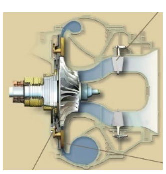
## Single Stage Centrifugal Blowers

- Single machined impeller
- Standard induction motor (constant speed)
- Gearing system increases motor speed to impeller (20–30,000 rpm)
- Used at small to large WWTPs
- Proven / reliable operation
- Efficient over wide range of air flows
- Somewhat noisy
- Little vibration
- Complex lubrication system



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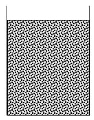
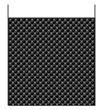
## Gas transfer devices

Mechanical (surface) aerators of activated sludge process treating wastewater

Fine bubble



Fine bubble diffuser



Course bubble diffuser

82

82

## Diffuse Air – Oxygen Supply

Coarse bubble diffuser

Fine bubble diffuser

High efficiency fine bubble diffusers

- 15-25% transfer efficiency
- Porous diffusers (ceramic, flexible membrane)
- Jet mixers (discharge through nozzles)

Non-porous course bubble diffusers

- 5-8% gas transfer efficiency
- Perforated pipes

83

83

## Coarse Bubble

- Application
  - Nearly every process and wastewater
  - Industrial applications - zero maintenance
  - Stainless steel construction
  - 30 year design life
- Efficiency
  - Spiral roll
  - 0.7-0.9% SOTE per ft submergence
  - 3-4 lb oxygen/kwh
  - 60% greater power than fine bubble fixed
- Maintenance
  - Near zero maintenance
  - Required maintenance - hardware, grit, diffusers
  - Inspection every 3-5 years

84

84

## Fine Bubble

- Application
  - Nearly every process and wastewater
  - Media sensitivity
  - Low oil membrane disc
  - Membrane 8-10 year minimum life
  - Ceramic 10–20 year life w/ PM
- Efficiency
  - Most efficient device
  - Greater than 2-3% SOTE per ft submergence
  - 8-10 lb oxygen/kwh
- Maintenance
  - Required maintenance - hardware, grit, leaks, diffusers
  - Ceramic annual cleaning
  - Membrane cleaning every 2 - 3 years

85

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## Fine Bubble

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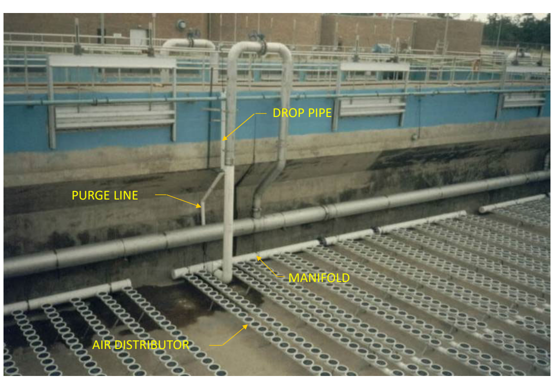


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87

If the influent BOD remains the same and you want to keep the same DO in the aeration tank and the MLSS has increased, what adjustment would you make to your aeration rate?

a. increase.
b. decrease.
c. no change.
d. switch to manual control

88

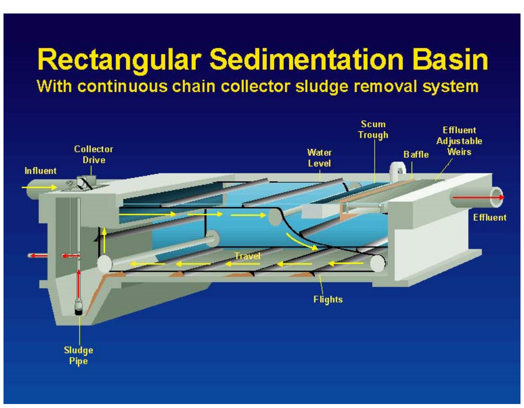
88

## Sedimentation

Configurations

89

89

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## Circular Sedimentation Basin

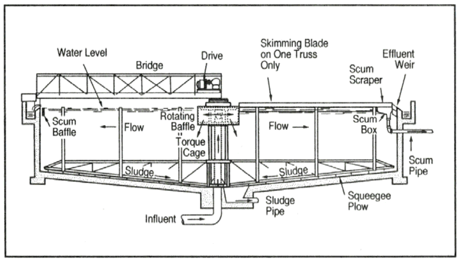


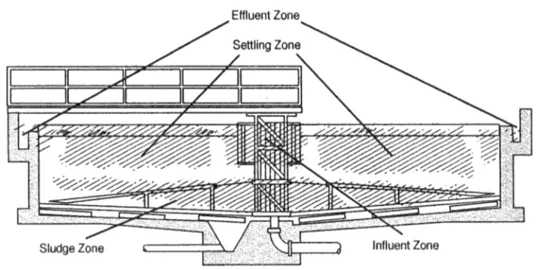

FIGURE 5-5 A typical circular sedimentation basin

Courtesy of FMC Corporation, MHS Division

91

91

## Zones in a Sedimentation Basin

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## Factors Affecting Settling Rate

- Water Temperature (4º C)
- Short Circuits
- Particle density
- Flow-thru velocity – Detention Time
- Solids charge
- Surface Loading Rate
- Weir Overflow Rate

93

93

## Re-Suspending Settled Solids

- Stilling Well too Close to Bottom
- Sludge Blanket too Deep
- High Flow Turbulence
- Side-Wall Short Circuiting

94

94

## Final Clarifier Capacity

- Clarifiers can be hydraulically and/or solids loading limited.
- Design MLSS concentration
- Higher MLSS concentrations may result in clarifier overloading.

95

95

## Final Clarifier Operation

- The sludge blanket is the layer of solids on the bottom of the clarifier
- Maintain final clarifier sludge blanket less than 12 inches.
- If blanket level rises, increase return sludge pumping rate.
- If there is no blanket, reduce return sludge pumping rate.
- A clear core sampler (Sludge Judge®) or an electronic device is most commonly used to measure blanket level

96

96

## Design Criteria

| | |
|---|---|
| **Surface Loading** | 0.2 – 0.5 gpm/sf; 300 – 800 gpd/sf |
| **Solids Loading** | 20 – 30 lbs/day/sf |
| **Water Depth** | 9 – 15 feet |
| **Detention Time** | 1.5 – 3 hours |
| **Width to Length** | 1:5 |
| **Weir Loading** | < 15 gpm/lf |

97

97

## Final Clarifier Observations


98

98

## Improving Clarifier Operation

- Monitor SVI of the Mixed Liquor.
  - Typically should be 150 mL/mg or less.
- If SVI increases due to filamentous bacteria or Nocardia, take corrective action:
  - Eliminate "low DO" (0.4 to 1.0 mg/L) regions of aeration tanks, which breed filaments
  - Increase the F/M ratio of aeration tanks by bypassing primary clarifiers or reducing the number of tanks in service.
  - Chlorinate return sludge to kill filaments.
  - Use spray water system to knock out Nocardia foam on surface.

99

99

## Excessive Filamentous Bacteria Growth

- May cause sludge settling problems.
- May cause excessive foaming.
- May result in both of above problems.

100

## Diagnosing Filamentous Problems

- Microscopic evaluation
- SSV or SVI
- Diluted SSV
- DOB

101

## Mixed Liquor Settling Characteristics

$$SVI = \frac{\text{settled volume of sludge (mL/L)}(10^3\,\text{mg/g})}{\text{suspended solids (mg/L)}} = \frac{mL}{g}$$

- Place a mixed liquor sample in a 1L or 2L cylinder
- Measure settled volume after 30 min
- Example: mixed liquor sample TSS = 3000 mg/L
- After 30 min, settled volume = 300 mL

$$SVI = \frac{(300\text{mL/L})(10^3\,\text{mg/g})}{3000\,\text{mg/L}} = \frac{100mL}{g}$$

- SVI = 100 mL/g – considered good settling sludge
- SVI varies between 50-150 mL/g in properly operating diffused air activated sludge plant

102

102

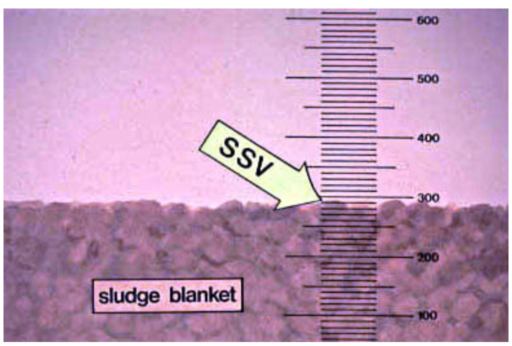
## Sludge Volume Index (SVI)

- A numerical expression of the settling characteristics of activated sludge
- SVI is expressed as the ratio of the settled volume in milliliters of activated sludge from a 100-mL sample in 30 minutes divided by the concentration of mixed liquor in milligrams per liter multiplied by 1,000.
- A good settling sludge (textbook value) is 100, but can commonly be between 80-150.

103

103

## Final Clarifier Observations

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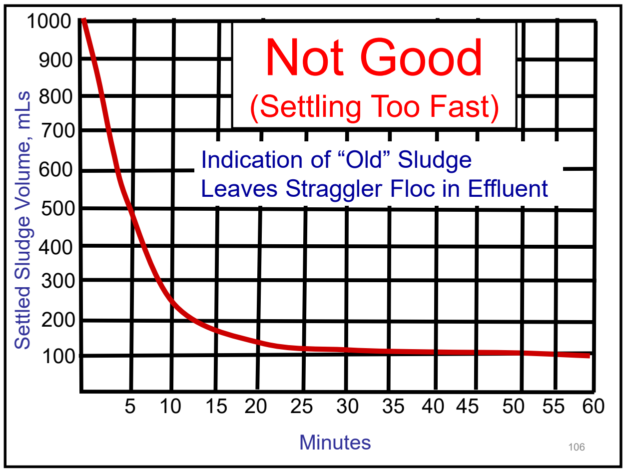



106


107

What does the sludge volume index (SVI) measure in an activated sludge system?

a. the density of the sludge.
b. the dissolved oxygen requirements of the sludge.
c. the comparison between the concentration and the settleability of the sludge.
d. the comparison between the relative age and the settleability of the sludge

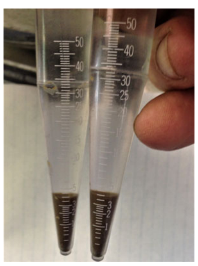
108

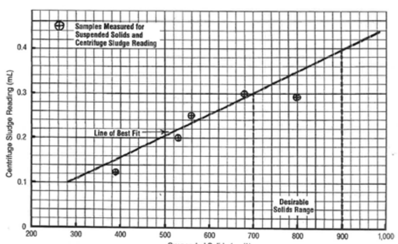
108

## SSV 100 % & 50/50 Diluted


109

## Centrifuge TSS Correlation






110

## Causes of Excessive Filamentous Bacteria

- Low MLDO
- High MCRT, low F/M
- Septicity
- Nutrient deficiency
- Low MLpH

111

What conditions can cause a filamentous problem in activated sludge?

a. low F/M ratio.
b. low dissolved oxygen in the aeration tank.
c. a toxic substance in the influent.
d. excessive aluminum sulfate addition.

112

112

## Control of Filaments

- Incorporate selector zone ahead of biological process.
- Add polymer to clarifier influent for settling problem.
- Add polymer to AT for foaming problem.
- Reduce MCRT.
- Controlled chlorination.
  - Apply to RAS for bulking
  - Spray on surface for foaming

113

### Chlorination for Bulking Control

- Insure proper dose rate to minimize impact on process performance- may start at 1-2 lbs/day/1,000 lbs VSS
- Choose appropriate application point
- Goal of 2-3 exposures/day for maximum effectiveness
- Chlorine dosing will be proportional to SVI
- SVI at which chlorination initiated or terminated is plant specific
- Some plants will require a minimal maintenance dose of chlorine to control SVIs

114

114

A method of controlling filamentous organisms in an activated sludge system is to dose the return sludge with which one of the following chemicals?

a. aluminum sulfate.
b. sodium hydroxide.
c. chlorine.
d. sulfur dioxide.

115

115

# Nitrification

Fundamentals

116

116

# Forms of Nitrogen

| FORM | REMOVAL PROCESS |
| --- | --- |
| • Organic-N | • Converts to ammonia forms; **a small soluble portion is non-reactive (1.0 mg/l)** |
| • Ammonia(um) ($NH_3$/$NH_4^+$) | • Most abundant form; converts to nitrites/nitrates under aerobic conditions (nitrification) |
| • Nitrite ($NO_2^-$)/Nitrate ($NO_3^-$) | • Converts to $N_2$ under anoxic (no oxygen) conditions (denitrification) |

117

117

## Forms of Nitrogen

- Ammonia(um) - $NH_3/(NH_4^+)$
- Organic Nitrogen - Org-N
- Nitrogen Gas $N_2\uparrow$
- Nitrite - $NO_2^-$
- Nitrate - $NO_3^-$

*TKN (Un-oxidized)*

*Oxidized*

Total Nitrogen (TN) = TKN + $NO_2$ + $NO_3$
TKN = Total Kjeldahl Nitrogen

118

118

1)The TKN test measures the following:

a) Org. N + Ammonia
b) Nitrate + Nitrite
c) Org. N + Nitrate
d) Ammonia + Nitrate

119

119

## What's Different for Nitrification ?

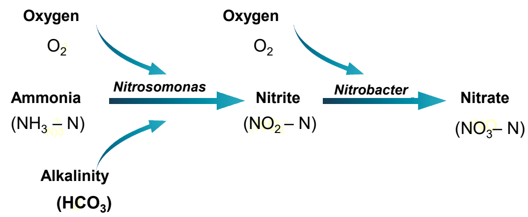
Need longer MCRT
Need more oxygen
Need more alkalinity
Need to be careful about inhibitory compounds
Temperature has a greater impact
pH has greater impact

120

120

## Nitrification

*The oxidation (as by bacteria) of ammonia and organic nitrogen to nitrites ($NO_2$) and the further oxidation of nitrites to nitrates ($NO_3$).*




121

121

## Nitrification – "Lots of Air"

$$NH_4^+ + O_2 \xrightarrow{\text{Nitrosomonas}} NO_2^- + H_2O + H^+$$

**Oxygen Required = 3.43 lb / lb N oxidized**
**Alkalinity Required = 7.14 lb as $CaCO_3$ / lb N oxidized**

$$NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} NO_3^-$$

**Oxygen Required = 1.14 lb / lb N oxidized**

For both reactions together:

**Total Oxygen Required = 4.57 lb / lb N oxidized**
**Total Alkalinity Required = 7.14 lb as $CaCO_3$ / lb N oxidized**

122

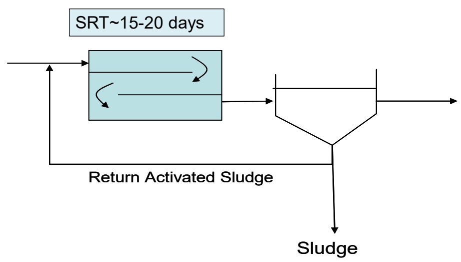
## Nitrification Processes

- Extended Aeration Activated Sludge
- 2-stage Activated Sludge System
- BNR/ENR Processes

123

123

## Extended Aeration for BOD Removal and Nitrification

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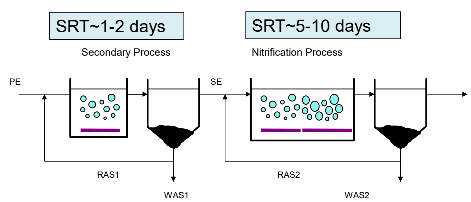
## Two Sludge System for BOD Removal and Nitrification

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125

## Conditions Necessary to Achieve Nitrification in the Activated Sludge Process

| | | |
|---|---|---|
| **Aerobic Mean Cell Residence Time** | **-** | **4 to 15 days** |
| **pH** | **-** | **6.5 to 8 optimal** |
| **Temperature** | **-** | **25° C for optimal nitrification** |
| **Dissolved Oxygen** | **-** | **>2.0 mg/l for optimal nitrification** |

126

126

What is the correct nitrification sequence?

a. ammonia to nitrite to nitrate.
b. ammonia to nitrate to nitrite.
c. nitrate to nitrite to ammonia.
d. nitrate to ammonia to nitrite.

127

127

## Nitrification Process Monitoring

- Key Factors:
  - Slow growth requires adequate **aerobic SRT or MCRT**
  - **DO** typically >2mg/L
  - **pH** 6.5- 8.0
  - Target effluent alkalinity of 50 to 75 mg/L as $CaCO_3$
  - Overall Reaction:
    - $NH_4^+ + 2\ O_2 \rightarrow NO_3^- + 2H^+ + H_2O$

128

128

## Nitrification Process Monitoring

- Oxygen requirements:
  - 4.6 mg/mg $NH_3$-N converted
  - Maintain DO in process between 2.0 – 4.0 mg/l
- Alkalinity requirements:
  - 7.1 mg/mg $NH_3$-N converted
  - Maintain alkalinity >70 mg/l $CaCO_3$

129

129

## Nitrification Process Monitoring

- **Key Factor 1**
  - Slow growth requires adequate aerobic SRT
  - MAINTAIN ADEQUATE SOLIDS INVENTORY
- **Key Factor 2**
  - Maintain target DO concentration
- **Key Factor 3**
  - Maintain target effluent alkalinity

130

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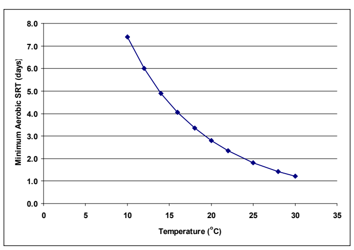
## Nitrification Process Monitoring

- **Key Factor 1**
  - Slow growth requires adequate aerobic SRT
  - MAINTAIN ADEQUATE SOLIDS INVENTORY

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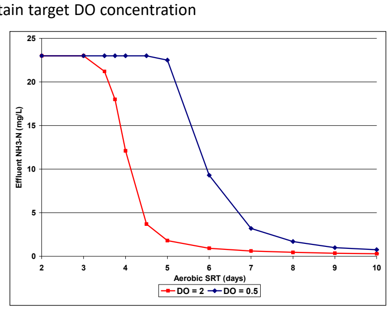
## Nitrification Process Monitoring

- **Key Factor 2**
  - Maintain target DO concentration

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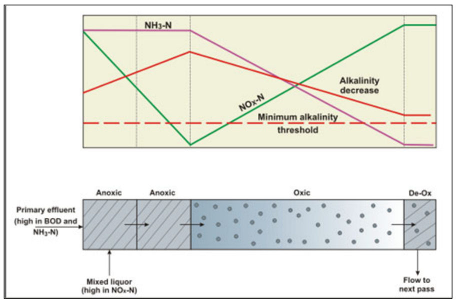
## Nitrification Process Monitoring

- **Key Factor 3**
  - Maintain target effluent alkalinity




133

133

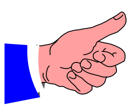
## Effect of Temperature on Nitrification

**As temperature increases, nitrifier growth rate increases (within the range of 4° C to 35° C).**

**T ↑ μ ↑**

**As nitrifier growth rate increases, required MCRT decreases.**

**μ ↑ MCRT ↓**



**<u>Rule of Thumb</u>:**
**For every 10°C increase in temperature, nitrifier growth rate doubles, required MCRT is cut in half and required MLSS concentration is also reduced.**

134

134

As the biomass activity slows in the winter, what action should the operator take?

a. maintain an older sludge
b. maintain a younger sludge
c. increase the sludge wasting rate
d. increase the sludge blanket in the clarifier

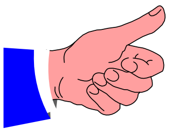
135

135

## Effect of Dissolved Oxygen Concentration on Nitrification

**As dissolved oxygen increases, nitrifier growth rate increases up to DO levels of about 5 mg/L.**

**DO ↑ μ ↑**



**<u>Rule of Thumb</u>:**
**Maintain dissolved oxygen concentration at 2.0 mg/l or higher for optimum nitrification.**

136

136

## Effect of pH and Alkalinity on Nitrification

**Nitrification consumes alkalinity and lowers pH in the activated sludge mixed liquor.**

**pH below 6.5 or above 8.0 can significantly inhibit nitrification.**

**<u>Rules of Thumb</u>:**
**Maintain pH in the range 7.5 - 8.5, 8.4 is optimum for nitrification.**

**Overall alkalinity consumption is generally less than the theoretical 7.14 lbs as $CaCO_3$ per lb of ammonia-N nitrified.**

137

137

What are three of the most important operational variables in the activated sludge system?

a. BOD loading, temperature, return sludge rate.
b. BOD loading, pH, solids settleability.
c. BOD loading, quantity of microorganisms, dissolved oxygen.
d. BOD loading, return sludge rate, pH.

138

138

## Alkalinity Supplementation

- Sodium Hydroxide (caustic soda) - $NaOH$
- Calcium Hydroxide (Lime) - $Ca(OH)_2$
- Calcium Oxide (quick lime) - $CaO$
- Magnesium Hydroxide – $Mg(OH)_2$
- Sodium Carbonate (soda ash) – $Na_2CO_3$
- Sodium Bicarbonate $NaHCO_3$

139

## Indications of Nitrification Issues

- Increased ammonia levels in effluent
- Without effective nitrification, subsequent denitrification will not occur resulting in poor TN removal
- **Nitrification is the most sensitive step in the nitrogen removal process**
- Multiple culprits for decreased nitrification
    - Solids Inventory (MLSS, SRT/MCRT, WAS)
    - D.O.
    - pH (alkalinity)
    - Temperature - Mixed Liquor
    - Inhibition

140

140

## Nitrification- Operational Problems

- **If effluent ammonia-nitrogen is above the goal:**
    - Verify adequate DO in the aerobic zones.
    - Verify adequate alkalinity in the Aeration Tank effluent.
    - Consider if inhibitory compounds could be present.
    - If none of the above are true, increase aerobic MCRT.

141

141

## Nitrification- Operational Problems (cont.)

- **Ways to raise aerobic MCRT:**
  - Increase total MCRT by reducing sludge wasting, but do not allow rising MLSS to exceed clarifier capacity.
  - Increase percent volatiles (MLVSS) without increasing total MLSS by reducing the amount of inerts entering system through chemical feeds and sidestream loads (i.e. from septage or sludge thickening/digestion).
  - Increase MCRT without raising MLSS by bringing more aeration tanks on-line.
  - Increase aerobic MCRT without raising total MCRT by operating switch zones in the aerobic mode

142

142

## Nitrite Production

- During periods of partial nitrification, nitrites ($NO_2$-N), which are normally not present in the secondary effluent, may be present at measurable concentrations.
- Nitrites can cause very high chlorine demand for effluent disinfection.
- Avoid nitrite production by achieving complete nitrification.

143

143

## Nitrification- Operational Problems

- **If effluent ammonia-nitrogen is above the goal:**
  - Verify adequate DO in the aerobic zones.
  - Verify adequate alkalinity in the AT effluent.
  - Consider if inhibitory compounds could be present.
  - If none of the above are true, increase aerobic MCRT.

144

144

# Nitrification Problems

| Possible Causes | Solution |
|---|---|
| Insufficient MCRT | Increase MCRT to establish nitrification by reducing sludge wasting |
| Insufficient DO in aerobic zone (< 2.0 mg/L goal) | Increase aeration by adjusting air valves, increasing blower output, or turning on another blower. |
| Insufficient alkalinity | Add supplemental alkalinity to maintain 50 mg / L as $CaCO_3$ in effluent |
| Chemical inhibition of nitrifiers | Trace source of improper discharge of nitrification inhibitors and eliminate at source |

145

145

Which of the following decreases in the nitrification process?

a.biomass.
b.nitrites.
c.nitrates.
d.alkalinity.

146

146

# Activated Sludge Processes

Monitoring & Control

147

147

## Young Sludge

- **Start-up or High BOD Load**
- **Few Established Cells**
- **Log Growth**
- **High F:M**
- **Low MCRT**

148

148

## Young Sludge

Poor Flocculation
Poor Settleability
Turbid Effluent

White Billowing Foam

149

149

In a new activated sludge plant, billows of white sudsy foam appear on the aeration tank. What process control step should the operator take?

a. increase RAS.
b. decrease RAS.
c. increase WAS.
d. decrease WAS.

150

150

## Old Sludge

- Slow Metabolism
- Decreased Food Intake
- Low Cell Production
- Oxidation of Stored Food
- Endogenous Respiration
- Low F:M
- High CRT
- High MLSS

151

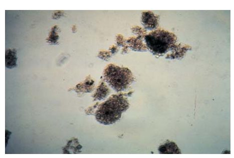
151

## Old Sludge

Dense, Compact Floc

Fast Settling

Straggler Floc



152

152

## Aeration

153

153

## Aeration Tank Observations

- Even mixing pattern from diffusers
- Foam – visible amounts
- Color of mixed liquor – chocolate to dark brown
- Odor – musty or earthy odor

154

154

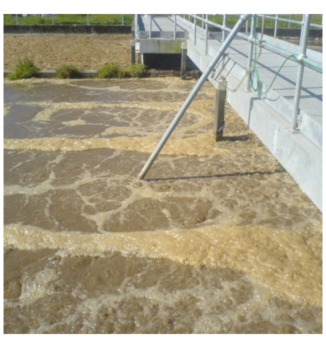
## Aeration Tank Observations

- Foam:
  - Low MCRT – off white, small amounts
  - High MCRT – dark brown, larger amounts
- Color of mixed liquor:
  - Low MCRT - chocolate brown
  - High MCRT – dark chocolate brown

155

155

## Typical Foam with D.O. Probe



156

156

## Spray Wash for Foam Control

157

157

What are the characteristics of a healthy activated sludge?

a. black color, dark foam, unpleasant odor.
b. black color, light foam, musty odor.
c. brown color, light foam, musty odor.
d. brown color, dark foam, unpleasant odor.

158

158

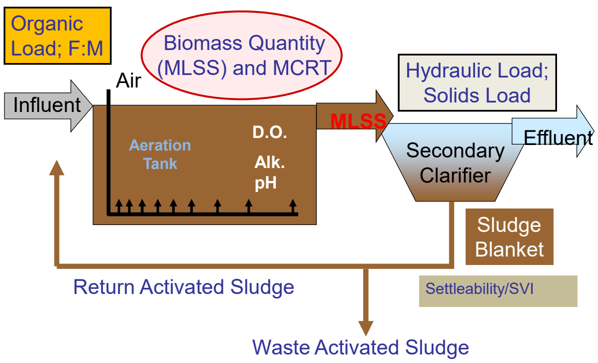
## Loading Rates

- Hydraulic loading rate – $gpd/ft^2$
  - Sedimentation tanks
  - Thickeners
- Solids loading rate – lbs TSS per $day/ft^2$
  - Sedimentation tanks
  - Thickeners
- Organic loading rate – lbs BOD per day
  - Activated sludge - lbs BOD/day/1000 $ft^3$ of aerator
  - Trickling Filters/RBCs - lbs $BOD/day/ft^2$

159

159

## Operating Parameters




160

160

## Operating Parameters

- MLSS/MLVSS, mg/l
- Dissolved oxygen, mg/l
- pH and alkalinity
- BOD, TSS, TN, and TP
- Sludge Volume Index (SVI)

} Analytical data

- Aeration detention time, hours
- Organic loading, lbs BOD/1000 $ft^3$ of aeration tank
- Food/Mass ratio (F/M), lbs BOD/lbs MLSS or MLVSS
- Mean Cell Residence Time (MCRT), days
- WAS rate, $Q_w$
- RAS, $\%Q_{in}$

} Flow data

161

161

## Mixed Liquor Suspended Solids

- The concentration of suspended solids in an aeration tank, expressed in mg/L.
- MLSS consists mostly of microorganisms and non-biodegradable suspended matter.
- The volatile portion is used as a measure of microorganisms present in the aeration tank.
- Total pounds of MLSS in an aeration tank can be calculated by multiplying the MLSS concentration (mg/L) in the aeration tank by the tank volume (MG), and then multiplying the product by 8.34 (lbs/gal).

162

162

An activated sludge MLVSS typically has what percentage volatile matter?

a. 90%
b. 70 - 80%
c. 40 - 60%
d. less than 40%

163

163

## Organic Loading

- Organic loading is the amount of biodegradable material that exerts an oxygen demand on the biological treatment process.
- The organic strength of the wastewater is usually measured as biochemical oxygen demand (BOD) in milligrams per liter (mg/L).
- An organic overload is an event, which significantly increases the organic loading (BOD) to the aeration basin above normal influent organic loading conditions.

164

164

## Organic Volumetric Loading Rate

- Pounds BOD/day per 1,000 $ft^3$ of aeration tank

$$\text{Lbs/day/1,000 ft}^3 = \frac{\text{Qin x BODin, mg/l x 8.34}}{V_t}$$

where: $Q_{in}$= influent wastewater flow, MGD
$BOD_{in}$ = influent BOD concentration, mg/l
$V_t$= aeration tank volume, 1,000 $ft^3$

165

165

## Food-to-Microorganism Ratio

- Food to microorganism ratio (F:M or F/M) is the amount of food (BOD5) provided to the microorganisms (MLVSS) in the aeration basins
- F:M is determined by dividing the pounds of influent $BOD_5$ by the pounds of mixed liquor volatile suspended solids (MLVSS) in the aeration tank

166

166

## Food to Microorganism Ratio

$$\frac{F}{M} = $$

$$= \frac{\text{Lbs of BOD}}{\text{Lbs of MLVSS}}$$

**Calculate Often to Monitor/Control**

•Don’t rely on a single day’s SRT/MCRT

•Use a running average over a period of time
Monthly (Minimum)
Weekly (Better)
Use Moving Average

167

167

If the F/M ratio is increased to an aeration basin and the operator wants to maintain the same dissolved oxygen level in the aerator, what action would the operator take?

a. increase the aeration rate.
b. decrease the aeration rate.
c. decrease the wasting rate.
d. increase the return sludge rate.

168

168

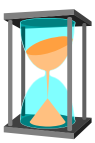
## MCRT

- Mean cell residence time (MCRT) equals the pounds of solids in the system (in the aeration tank and secondary clarifier) divided by the pounds of solids leaving the system (pounds of waste activated sludge plus pounds of clarifier effluent solids).
- Mean Cell Residence Times:
  - BOD removal, NO nitrification - 1 to 3 days
  - Complete nitrification - 8 to 12 days

169

169

## SRT/MCRT Calculations



The average length of time, in days that an organism remains in the secondary treatment system

$$\frac{\text{Biomass in System, pounds}}{\text{Pounds of solids leaving System per day}}$$

$$\frac{\text{Biomass in System, pounds}}{\text{Pounds TSS wasted + Pounds TSS lost in eff.}}$$

170

170

## SRT or MCRT

**SRT** - Solids Residence Time (Reactor only)

$$\frac{\text{Pounds of MLSS in aeration tanks}}{\text{Pounds TSS wasted + Pounds TSS lost in eff.}}$$

**MCRT** - Mean Cell Resident Time (Reactor and Clarifier)

$$\frac{\text{Pounds of MLSS in aeration and clarifier tanks}}{\text{Pounds TSS wasted + Pounds TSS lost in eff.}}$$

$$\frac{\text{MLSS, mg/l x ( aeration + clarifier Vols.) x 8.34}}{\text{Pounds TSS wasted + Pounds TSS lost in eff.}}$$

171

171

## Sludge Volume Index (SVI)

- A numerical expression of the settling characteristics of activated sludge
- SVI is expressed as the ratio of the settled volume in milliliters of activated sludge from a 100-mL sample in 30 minutes divided by the concentration of mixed liquor in milligrams per liter multiplied by 1,000.
- A good settling sludge (textbook value) is 100, but can commonly be between 80-150.

172

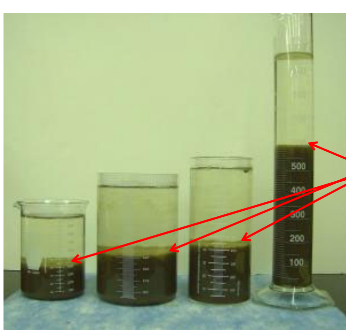
172

## Settled Sludge Observations

March 2016 Wastewater - Day 4 of 8

173

## Side-by-Side Comparisons




Note the higher result in the 1,000 ml graduated cylinder

174

174

## Flow and Hydraulic Retention Time

- Hydraulic load is the flow entering the plant, measured in million gallons per day (MGD).
- AKA: detention time
- The **hydraulic retention time** (**HRT**), is a measure of the average length of time wastewater remains in a tank
- HRT, hours = $\dfrac{\text{Volume of tank, MG}}{\text{Flow, MGD} \div \text{24 hours/day}}$

175

175

## Return Activated Sludge

- The settled activated sludge (biomass) that is collected in a secondary clarifier and returned to the secondary aeration process to mix with incoming wastewater
- The RAS pumps a concentrated population of microorganisms back into the aeration basin
- Centrifugal pumps are commonly used in the RAS line

176

176

## Waste Activated Sludge

- The activated sludge (excess biomass or cell mass) removed from the secondary treatment process.
- For most treatment plants, this will be a portion of the Return Activated Sludge (RAS) flow stream.

177

177

What is the preferred method of wasting activated sludge?

a. once per hour.
b. once per shift.
c. once per day.
d. slowly, continuously.

178

178

## Nitrification Process Monitoring

- Oxygen requirements:
  - 4.6 mg/mg NH3-N converted
  - Maintain DO in process between 2.0 – 4.0 mg/l
- Alkalinity requirements:
  - 7.1 mg/mg NH3-N converted
  - Maintain alkalinity >70 mg/l $CaCO_3$

179

179

## Indications of Nitrification Issues

- Increased ammonia levels in effluent
- Without effective nitrification, subsequent denitrification will not occur resulting in poor TN removal
- **Nitrification is the most sensitive step in the nitrogen removal process**
- Multiple culprits for decreased nitrification
  - Solids Inventory(MLSS, SRT/MCRT, WAS)
  - D.O.
  - pH (alk)
  - Temp.
  - Inhibition

180

180

## Nitrification- Operational Problems

- **If effluent ammonia-nitrogen is above the goal:**
  - Verify adequate DO in the aerobic zones.
  - Verify adequate alkalinity in the AT effluent.
  - Consider if inhibitory compounds could be present.
  - If none of the above are true, increase aerobic MCRT.

181

181

## Nitrification- Operational Problems

- **Ways to raise aerobic MCRT:**
  - Increase total MCRT by reducing sludge wasting, but do not allow rising MLSS to exceed clarifier capacity.
  - Increase percent volatiles (MLVSS) without increasing total MLSS by reducing the amount of inerts entering system through chemical feeds and sidestream loads (i.e. from septage or sludge thickening/digestion).
  - Increase MCRT without raising MLSS by bringing more aeration tanks or RBCs on-line.
  - Increase aerobic MCRT without raising total MCRT by operating switch zones in the aerobic mode

182

182

## Nitrite Production

- During periods of partial nitrification, nitrites ($NO_2$-N), which are normally not present in the secondary effluent, may be present at measurable concentrations.
- Nitrites can cause very high chlorine demand for effluent disinfection.
- Avoid nitrite production by achieving complete nitrification.

183

183

## SRT/MCRT Calculations

- **"Biomass in System, pounds"**
  - Typically, biomass in the aeration tanks
  - Biomass in the clarifiers are included in calculations
  - Active biomass is approximated by MLVSS
  - Since %VS in MLSS, WAS, and effluent TSS is the same, MLSS can be used in SRT/MCRT calculations

184

184

## MCRT Example

For an activated wastewater treatment plant with an effluent flow of 2.0 mgd, MLSS concentrations of 2500, an aeration tank volume of 1.0 MG, a final clarifier volume of 0.25 MG, the sludge wasted is 1500 lbs/day and effluent solids are 5 mg/l. Calculate the MCRT for this process.

$$\text{MCRT, days} = \frac{\text{Solids in the System}}{\text{Solids leaving System}}$$

$$\text{MCRT, days} = \frac{2500 \text{ mg/L} \times (1.0 \text{ MG} + 0.25 \text{ MG}) \times 8.34}{1500 \text{ lbs/day} + 5 \text{ mg/L} \times 2.0 \text{ MGD} \times 8.34}$$

$$= \frac{2{,}500 \times 1.25 \times 8.34}{1500 + 83.4} = \frac{26{,}063}{1{,}583} = 16.5 \text{ days}$$

185

185

## MCRT - Sludge Wasting

- Waste sludge from the process every day to maintain SRT/MCRT goals
- Waste sludge pumps can be controlled automatically or set manually
- Extend sludge wasting period as long as possible by running waste sludge pumps at a slow rate – this will prevent sudden changes from impacting the biological process

186

186

## MCRT – Running Average

- For example, if SRT or MCRT is about 7 days, use a 7-day running average
- A 3-day rolling average is acceptable

187

187

## F/M Ratio

- Food/active biomass = BOD Loading/MLVSS
- F/M = Lbs $BOD_{in}$ per day/Lbs MLVSS
- F/M = $Q_{in}$ x $BOD_{in}$ x 8.34/($V_t$ x MLVSS, mg/l x 8.34)

Where:

Q = aeration influent wastewater flow, MGD

$BOD_{in}$ = aeration influent BOD concentration, mg/l

$V_t$ = aeration tank volume, MG

MLVSS = volatile suspended solids in aeration tank, mg/l

188

188

What is the name of the activated sludge process control strategy that compares the amount of the influent BOD to the size of the biomass?

a. mean cell residence time (MCRT).
b. sludge age.
c. sludge volume index (SVI)
d. food to mass ratio (F/M).

189

189

## Detention Time, hours

- Time for wastewater flow to fill up a tank, or to completely replace the contents of a tank
- Detention time = Vt/Qin, hours
  - Where: $V_t$ is in MG
    Qin is in MGD
- Typically, flow is in MGD, so flow must be converted to MG per hour:

  e.g., MGD/(24 hours/day)

190

190

## Activated Sludge Math

Math:
- SVI
- Food to Microorganism Ratio
- Mean Cell Residence Time
- WAS Flow

- Calculate SVI for an activated sludge plant with a mixed liquor concentration of 2500 mg/l. The settled volume in the 1 liter settleometer is 200 ml's after 30 minutes.

- Calculate the F/M ratio for a 500,000 gallon aeration tank with a MLSS of 2500mg/l of which 80% is volatile. The flow is 2.5 MGD with a BOD of 200 mg/l.

- Given the following calculate the MCRT:

| Flow or Volume | TSS |
|---|---|
| Aeration Tank 0.50 MG | 2,500 mg/l |
| Clarifier 0.70 MG | 500 mg/l |
| WAS 0.04 MGD | 10,000 mg/l |
| Sec. Eff. 2.50 MGD | 20 mg/l |

- Given the following calculate the WAS Sludge Flow:

| Flow or Volume | TSS |
|---|---|
| Aeration Tank 0.50 MG | 2,500 mg/l |
| Clarifier 0.70 MG | 500 mg/l |
| WAS **? MGD** | 10,000 mg/l |
| Sec. Eff. 2.50 MGD | 20 mg/l |

191



191

## Questions?


192

192