Activated Sludge – Evolution to Nitrogen Removal

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Activated Sludge – Evolution to Nitrogen Removal

WWW 5880

7 contact hours
9 CC10 hours

What do you know about the various activated sludge configurations currently used, available, and evolving for activated sludge, BNR, and ENR processes? The objective of this class is to give activated sludge plant operators a more in-depth understanding of the activated sludge process. With this understanding, effluent quality variability and process energy usage can be reduced. Topics to be presented include: wastewater characterization, biological N & P removal, the importance of sludge quality, measuring and controlling sludge quality, WAS flow control, RAS flow optimization, secondary clarifier performance diagnostic testing. Specifically, types of aeration diffusers (mechanical, fine bubble, and membranes) and blowers (positive, multistage, single stage, and high speed) will be addressed. The influence of MCRT and MLSS will also be addressed as to the efficiency, ease (or difficulty) and cost of aeration. Finally, helpful operating hints will be provided based on experiences from operating facilities.

1. Describe the activated sludge process in detail.
2. Identify methods for nitrogen and phosphorus removal
3. Identify how to measure and control activated sludge quality.
4. Describe how to complete secondary clarifier performance diagnostic testing.
5. Discuss the influence of MCRT and MLSS as it relates to efficiency.

Agenda:

1. Introduction (30 minutes)
2. Activated Sludge Process (60 minutes)
    a. Effluent quality variability
    b. Process energy
3. Wastewater Characterization (90 minutes)
4. Biological N & P Removal (90 minutes)
5. Sludge Quality (60 minutes)
    a. Measuring
    b. Controlling sludge quality
6. WAS flow control and RAS flow optimization (30 minutes)
7. Secondary clarifier performance diagnostic testing (30 minutes)
    a. Aeration diffusers
    b. blowers
8. MCRT and MLSS (30 minutes)

MCeT
environmental, health, and safety training
Maryland Center for Environmental Training
at the
COLLEGE of SOUTHERN MARYLAND

Evolution of BOD Removal to Nutrient Removal using
Activated Sludge Processes

Process Training Sessions

Before class starts, please:
- **Sign in** on Attendance Sheet
- **Fill out** Registration Form, if appropriate

During class, please:
- **Asks questions**
  - Feel free to get up and leave the classroom at any time (i.e., rest rooms, phone calls, etc.)
- **Answer questions** on post test

After class, please:
- **Fill out** a Class Evaluation
- **Pick up** Attendance Card, if appropriate

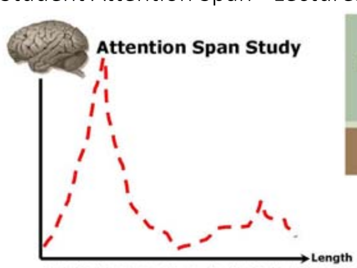
Housekeeping

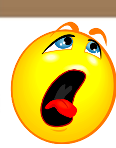
- 1–day class
- Start class – 8:00 am
- 10-minute Breaks – every hour
- Lunch ~ 11:30 am – 12:30 pm
- End class ~ 3:30 to 4:00 pm

Instructor Expectations

- Begin and end class on time
- Be interactive – participate at your own comfort level
- Share experiences and needs
- Less lecture, more discussions
- Keep it simple
- ***Make this an enjoyable and informative experience!***

Student Attention Span - Lectures





13

Discussions

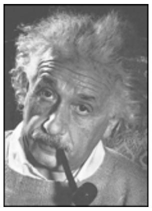
- Student involvement in class discussions is encouraged:
  - To keep students attentive
  - To help students retain information

The <u>Guiding</u> Expectation

"Things should be made as simple as possible -- but no simpler."

Albert Einstein

www.physik.uni-frankfurt.de/~jr/physpiceinstein.html



Ground Rules

- Discussion is encouraged; share experiences
- Use terms we all can understand
- Everyone is different, so please show respect for others in the room
- Express opinions - of things, not people
- Maintain confidences

Ice Breaker

- Before we start, let's introduce ourselves.
  - Name,
  - What do you do, and
  - What are your learning needs?

Introduction

Objectives, Focus, and Agenda

Purpose of Today's Class

- Discuss:
  - Activated sludge history and process fundamentals
  - Activated sludge processes for:
    - BOD Removal
    - Nutrient (TN and TP) Removal
  - Instrumentation, Control, and Automation (ICA)

Purpose of Today's Class

- To discuss the Activated Sludge biological treatment processes
- To discuss Activated Sludge process parameters:
  - Hydraulic and organic loadings
  - F:M/MCRT/SRT
  - Detention times
  - Instrumentation and automation
- To discuss the evolution of Activated Sludge processes – from BOD removal to nutrient removal

Participant Focus

- What information can you use at your work?
  - Aeration and sedimentation fundamentals
  - Activated Sludge troubleshooting
  - Meeting BOD, TSS, nutrient discharge standards
- What information can you contribute to the discussion?
  - Aeration practices
  - Solutions to sludge settling issues

Class Outline

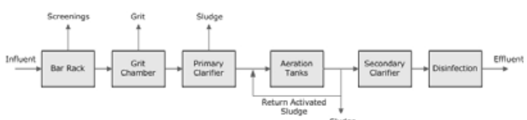
- Introduction
- Activated Sludge
- Nitrification/Denitrification
- BNR – Biological Nutrient Removal
- ENR – Enhanced Nutrient Removal
- Phosphorus Removal

Introduction

Definitions and Acronyms

Activated Sludge WWTP

- Wastewater (e.g. municipal wastewater) goes through several stages in which different compounds are removed



Definitions

- **Bar Rack** – where coarse solids are removed, such as sticks, rags, and other debris in untreated wastewater by interception. Use fine screens can remove even floatable matter and algae
- **Grit Chamber –** where grit is removed consisting of sand, gravel, cinders, or other heavy solid materials that have settling velocities or specific gravities substantially greater than those of the organic putrescible solids in wastewater

Definitions

- **Primary Clarifier –** where water has a certain retention time so that the heavy organic solids can settle out (suspended solids). Efficiently designed and operated primary sedimentation tanks should remove from 50 to 70 percent of the suspended solids and 25 to 40 percent of the BOD

Definitions

- **Aeration Tank –** where the mixed liquor is aerated. By aerating the mixed liquor, the soluble substrate becomes biomass solids
- **Secondary Clarifier –** where biomass solids settle out
- **Disinfection -** where chlorine or UV is used to make effluent free of disease-causing organisms

Biological Treatment

- Activated Sludge
  - MLSS – Mixed Liquor Suspended Solids
  - MLVSS – Mixed Liquor Volatile Suspended Solids
  - WAS – Waste Activated Sludge
  - RAS – Recycled Activated Sludge
- Activated Sludge Process Control:
  - DT – Detention Time , Tank volume/flow rate, V/Q, hours
  - MCRT/SRT – Mean Cell/Solids Retention Time, days
  - F:M – Food-to-Mass ratio, BOD/MLVSS
  - SV – Sludge Volume after 30 minutes
  - SVI – Sludge Volume Index, SV x 10,000/MLSS

Biological Treatment

- BNR/ENR – Biological/Enhanced Nutrient Removal
  - Anaerobic – Soluble BOD uptake and Phosphorus Release
  - Anoxic – Denitrification
  - Aerobic - Nitrification
  - IR or NR– Internal Recycle /Nitrate Recycle

Acronyms

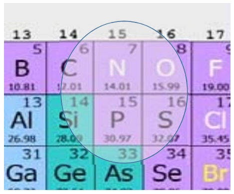
- BNR – Biological Nutrient Removal
- ENR – Enhanced Nutrient Removal
- TMDL – Total Maximum Daily Loading
- MLE – Modified Ludzack-Ettinger BNR Process
- IFAS – Integrated Fixed Film Activate Sludge
- MBBR – Mixed Bed Bioreactor
- COMAMMOX – COMplete AMMonia OXidation
- ANAMMOX – ANaerobic AMMonia OXidation

Microorganisms

- **Aerobic** (Oxic) - Organisms requiring, or not destroyed, by the presence of free oxygen
- **Anoxic**: Organisms requiring , or not destroyed, by the absence of free oxygen; nitrates (NO_3) are present.
- **Anaerobic** - Organisms requiring, or not destroyed, by the absence of free oxygen and NO_3
- **Facultative** - Organisms able to function both in the presence or absence of free oxygen
- **Heterotrophic** - Organisms that use organic materials as their source of cell carbon
- **Autotrophic** - Organisms able to use carbon dioxide and other inorganic matter as their source of carbon
- **Filamentous** – Bulking organisms that grow in thread or filamentous form

Nutrients - Overview

Part of the Periodic Table



- ✓ Both Phosphorus and Nitrogen are considered essential for plant and animal life
- ✓ Both are called nutrients

Introduction

1972 Clean Water Act (CWA)

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

Clean Water Act (CWA)

- Water Quality Concerns:
  - BOD (Biological treatment)
  - TSS (Sedimentation and filtration)
  - Coliforms (Disinfection)
  - Nutrients:
    - Nitrogen (Nitrification and denitrification)
    - Phosphorus (Biological uptake and chemical precipitation)

Water Use

- WWTP discharge standards are set to meet water quality standards:
  - In waterways
    - Aquatic and marine life
    - Water contact sports
      - Swimming
      - Boating
      - Fishing
  - For downstream water users:
    - Domestic water supplies
    - Industrial water supplies
    - Agriculture water supplies

Clean Water Act (CWA)

- EPA can/will impose more stringent **<u>water quality discharge standards</u>** for contaminants:
  - If chemical, physical, and biological integrity of the receiving water requires more removal; e.g., BNR to ENR program in the Chesapeake Bay
  - As new technologies become available to offer cost effective solutions to water quality problems; e.g., automated SBRs for WWTPs < 0.5 MGD

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

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 contaminants** to eliminate infectious diseases
- Required levels of treatment are based on NPDES regulations as prescribed in issued discharge permits

Nutrient Removal "Driver"

Chesapeake Bay Regulations

Nutrient Removal

- **Why remove Nutrients (nitrogen and phosphorus):**
  - Nutrients contribute to algae growth
  - Excess algae growth (Eutrophication) causes water quality issues:
    - Loss of water clarity
    - Limitation on sunlight penetration
    - Oxygen depletion
    - Fish and marine life die-off
    - Submerged aquatic vegetation (SAV) die-off

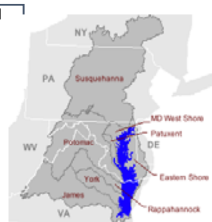
Ecosystems Affecti the Bay

Chesapeake Bay Watershed

- The largest estuary system in the contiguous United States
- Watershed is almost 64,000 square miles
- Surface area of the Bay is 3,830 square miles
  - Of these, 153 square miles are tidal fresh waters
  - 3,562 square miles constitute the mixing zone
  - 115 square miles are salt waters

The Chesapeake Bay Program

- In 1983, the Chesapeake Bay Program (CBP) created
  - In a 1987 Agreement, water quality targets (40% less than 1985 conditions) for 2000 were established
- Chesapeake Bay 2000 Agreement
  - USEPA, MD, VA, DC, PA and the Chesapeake Bay Commission – Signatories to agreement
  - USEPA has the lead on setting water quality standards for the Bay
  - States develop plans (Tributary Strategies) and implement actions
  - 2010 - Target Date to meet water quality standards, remove the Bay from the impaired waters list, and to avert the need for TMDLs
- **Beyond 2010 – TMDLs and consent decrees**
  - **2017 is new interim target date**
  - **2025 is new target date**



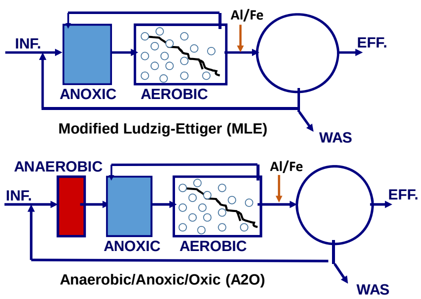
BNR Program

- EPA created the Chesapeake Bay Program in 1983; first Chesapeake Bay agreements signed in 1987
- BNR Programs initiated by Bay states
- For WWTPs greater than 0.5 mgd:
  - 95% of wastewater discharged into the Bay
  - Grant funding available for WWTP upgrades
- WWTP discharge goals:
  - Reduce TP from ~ 6 mg/l to < 3.0 mg/l
  - Reduce TN from ~ 20 mg/l to < 8.0 mg/l

BNR Program

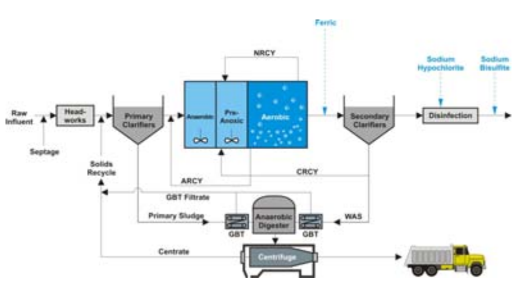
- To reduce total phosphorus concentrations, most WWTPs began add chemicals like $FeCl_3$ or alum
- To reduce total nitrogen concentrations, most WWTPs initiated a capital Improvement project to add "Pre" anoxic zones to already existing nitrification processes for partial denitrification

Biological Nutrient Removal



BNR

Typical BNR Activated Sludge System



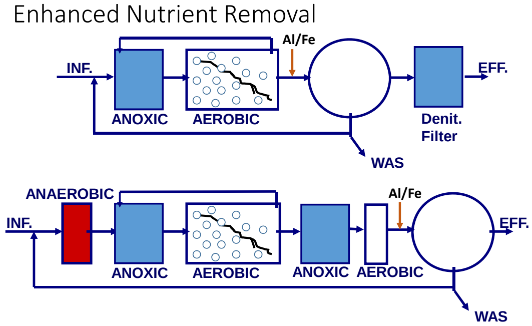
ENR Program

- New Chesapeake Bay Agreement enacted in 2000; ENR Program began in that same year
- For WWTPs greater than 0.5 mgd
  - 95% of wastewater discharged into the Chesapeake Bay
  - Grant funding available for upgrades
- WWTP discharge reduction goals:
  - Reduce TP from < 3.0 mg/l to < 0.3 mg/l
  - Reduce TN from < 8.0 mg/l to < 3.0 mg/l

ENR Program

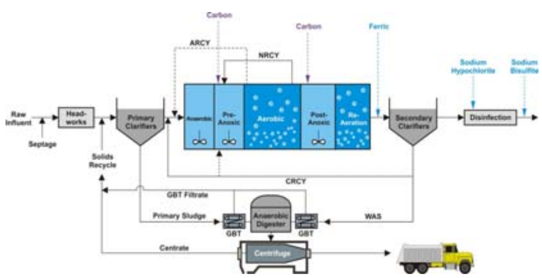
- To further reduce total phosphorus concentrations, most WWTPs began adding increased quantities of chemicals
- To further reduce total nitrogen concentrations, most WWTPs initiated a capital improvement project to add "Post" anoxic zones to already existing BNR facilities

Enhanced Nutrient Removal



ENR

Typical ENR Activated Sludge System



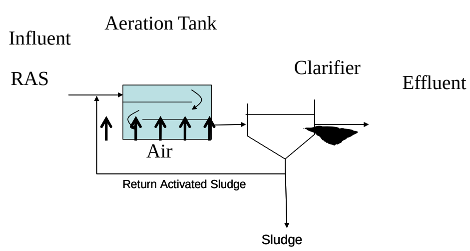
Enhanced Nutrient Removal (ENR)

- Over the past two decades, BNR facilities have been upgraded with automation and new technologies to improve nitrogen removal efficiencies:
  - Integrated Fixed Film Activated Sludge (IFAS) to enhance nitrification
  - Mixed Bed Bio-reactors (MBBR)
  - Biological Aeration Filters (BAF) for nitrification
  - Tertiary denitrification filters

Activated Sludge Process

Process Overview

Typical Activated Sludge Process



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)

Activated Sludge Processes

Activated sludge processes can 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**

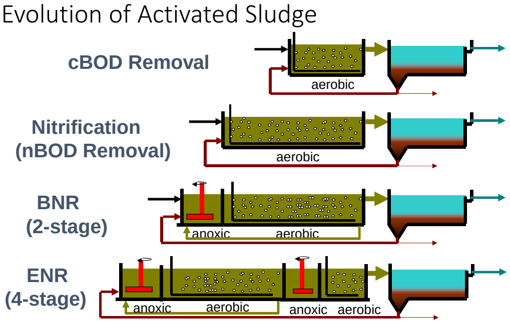
Process Combinations

- BOD removal (carbonaceous BOD)
- BOD removal and nitrification
- BOD removal and TN removal
  - Nitrification
  - Denitrification
- BOD removal, TN removal, and excess uptake of TP (e.g., Bio-P)

Brief Historical Overview

- 1912 – Aeration of MLSS experiments (US and England)
- 1915 – 1960s:
  - cBOD Removal
  - 30:20 (BOD_5:TSS) + nitrification - England
  - 30:30 (BOD_5:TSS) - US
  - Nitrification
- 1960s - 1970s – Phosphorus removal w/chemicals
- 1970s to 2000 – BNR development and application
- Past 30 years – BNR to ENR; filtration; automation

Evolution of Activated Sludge



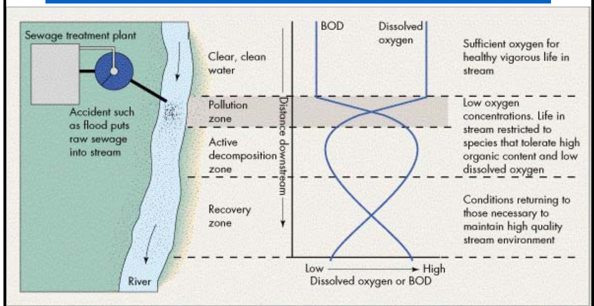
Wastewater Constituent Removal

- **TSS and cBOD Removal** in primary clarifiers and secondary bioreactors/clarifiers
- **TP removal** in primary, secondary, and tertiary
  - Particulate removal
  - Biological uptake
  - Chemical precipitation
- **Nitrification**: Ammonia-N conversion to nitrate-N
- **Denitrification**: Nitrate-N conversion to nitrogen gas

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^{o}C
    - DO uptake - 2.0 mg/l
    - DO remaining after five days -1.0 mg/l

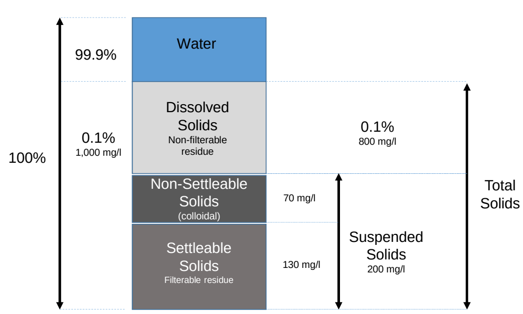
BOD Effects on Water Quality



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

Wastewater Solids



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 when alkalinity < ~ 60 mg/L
- Pathogenic organisms
  - E-coli indicator
  - Numbers are limited in permit

Key Wastewater Constituents

- Nutrients
  - TP – Total Phosphorus
  - TN – Total Nitrogen
- Phosphorus and Nitrogen compounds are nutrients that can stimulate production of excess algae in receiving waters
- Typical raw wastewater concentrations:
  - TP – 3 to 6 mg/l
  - TN – 30 to 45 mg/l

Nutrients

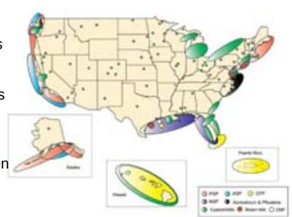
- TN – Total Nitrogen
  - Soluble and particulate
    - Organic nitrogen - N_{org}
    - NH_3 – Ammonia
    - NO_2 – Nitrite
    - NO_3 - Nitrate
- TP – Total Phosphorus
  - Soluble and particulate
    - PO_4 – Ortho-phosphorus
    - Organic
    - Polyphosphates

Nutrients

- TN – Total Nitrogen (N_{org} + NH_3 + NO_3 + NO_2)
- TP – Total Phosphorus (PO_4 + P_{org} + P_{poly})

Extent of N and P Impacts

- 14,000 Nutrient-related Impairment Listings in 49 States
- ~80% of Assessed Continental U.S. Coastal Waters exhibit eutrophication
- ~50% of streams have medium to high levels of nitrogen and phosphorus



Occurrence of Algae throughout the U.S.

Nutrient Removal

Nutrient	Removal Process

• Nitrogen	• Nitrification
	  • Ammonia Conversion
	  • NH_3^+-N to NO_3^-N
	  • Oxygen and alkalinity needed
	• Denitrification
	  • Nitrate Removal
	  • NO_3^--N to Nitrogen gas (N_2)
	  • Carbon source needed

• Phosphorus	• Physical Incorporation
	• Biological Uptake
	  • Conventional
	  • Excess
	• Chemical Precipitation

Nutrient Removal

FORM	Removal Mechanism	LOT[1], mg/L
TN		**< 1.5**
NH_3-N	Nitrification	< 0.1
NO_3-N	Denitrification	< 0.1
Org-N:		
Particulate	Solids Separation	< 0.5
Soluble	Ammonification	0.5 – 1.0
TP		**< 0.05**
Particulate	Solids Separation	< 0.05
Soluble	Biological uptake and chemical precipitation	< 0.05

Nutrient Discharge Limits - TN

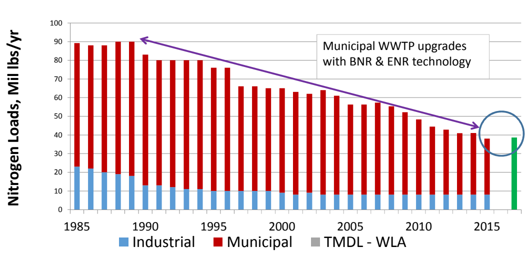
Typical **Total Nitrogen** Standards, mg/l

- Moderate 3.0 – 5.0 (BNR): > 1983
  Bay Target < 3.0 (ENR): > 2000
- Severe < 2.5
- Very Severe < 1.5
- LOT/SOA(a) < 1.0

(a) Limit of Technology/State of the Art

TN Loadings to the Chesapeake Bay Wastewater

(Million pounds/year)



Nutrient Discharge Limits - TP

Typical **Total Phosphorus** Standards, mg/l

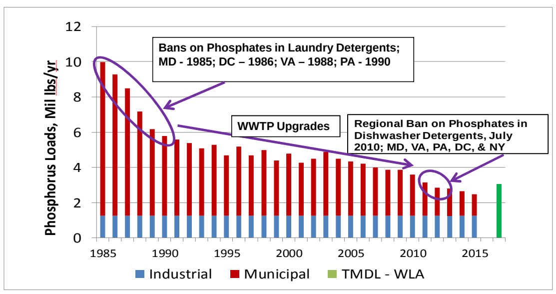
- Moderate 1.0 - 2.5 (BNR): > 1983

Bay Target < 0.3 (ENR): > 2000

- **Potomac River < 0.18 (ENR)**
- Very Severe < 0.1
- LOT/SOA(a) < 0.05

(a) Limit of Technology/State of the Art

TP Loadings to the Chesapeake Bay Wastewater



IC&A Drivers

- Instrumentation, control, and automation (IC&A)
  - Initiated in the 1970s
  - Major push in the 1980s
  - Meet nutrient regulatory requirements
- Improve process performance – BNR/ENR processes require effective DO control (enough but not too much, or none at all)

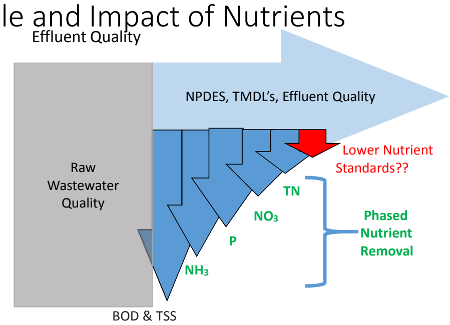
Nitrification-Related Process Instruments and Parameters

- Temperature
- Flow meters
- Flow rates:
  - Effluent
  - WAS
- Solids ret. time (SRT)
- pH/alkalinity
- Airflow distribution
- DO probe(s)
- DO conc., mg/L
- Ammonia probe(s)
- Ammonia conc., mg/L
- Nitrate probe(s)
- Nitrate conc., mg/L

Denitrification-Related Process Instruments and Parameters

- Temperature
- Flow meters
- Flow rates
  - Inflows
  - Internal Recycle
- pH/alkalinity
- DO probe(s)
- DO conc., mg/L
- Nitrate probe(s)
- Nitrate conc., mg/L

Role and Impact of Nutrients



How will future regulations affect Activated Sludge Processes?

Regulatory Challenges:

- Clean Water Act (CWA)
- Chesapeake Bay Program
- State Ordinances
  - Nutrients
  - Sludge
- Local Ordinances

October 2018 Evolution of Act. Sludge Process 76

Activated Sludge Process

Early History

Evolution of Act. Sludge Process 77

Need for Wastewater Treatment

- Epidemics (e.g., cholera) triggered interest in constructing sewage collection systems in large European cities:
  - Berlin: 1830
  - London: 1830
  - Hamburg: 1842

Evolution of Act. Sludge Process 78

Open Sewers – 1800s

Sewage “Farm” – Berlin 1900

- Early wastewater treatment systems were irrigation fields
- Problems with odors

History: Pre-Activated Sludge

- 1690 – Sewers (Paris, France)
- 1860 – Septic Tank (Louis Moureas)
- 1868 – Trickling Sand Filter Process (Edward Frankland)
- 1882 – Aeration of sewage (Argus Smith)
- 1911 – Chlorination (London, England)
- **1914 – Activated Sludge Process (Ardern and Lockett)**

Early History of Activated Sludge

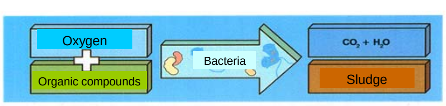
- 1898 - formation of the Royal Commission on Sewage Disposal in England
- In the early 1900's, England along with most of Europe and the US were seeking small footprint wastewater treatment solutions
- 1912 - Famous "30:20 + full nitrification" effluent standard was adopted in England
- New stringent BOD_5 effluent standard inspired creation of the activated sludge process

Early History of Activated Sludge

- In 2012, in the US, Clark and Gage at the Lawrence Experimental Station began looking at aerating suspended solids in wastewater
- Lawrence Experimental Station became known as "the Mecca of sewage purification"

Activated Sludge

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



Early History of Activated Sludge

- In 1912, Dr. Gilbert Fowler from the University of Manchester (England);
  - Began his activated sludge studies in Europe
  - Traveled to the Lawrence Experimental Station (LES) in Massachusetts, (USA)

Early History of Activated Sludge

- From 1913 – 1915, in England;
  - Lab-scale suspended biomass experiments were performed in England by Edward Ardern and his co-worker, William Lockett under the direction of Dr. Gilbert Fowler
  - In separate studies, Walter Jones of Jones and Attwood, Ltd. developed practical applications of the activated sludge process

Early History of Activated Sludge

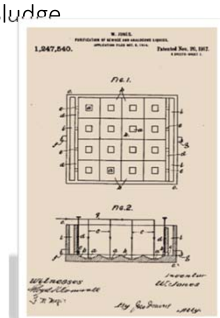
- 1914/1915 - Ardern and Lockett published their research findings on aeration of suspended solids (e.g., MLSS)
  - Added the concept of recycling sludge
  - First to use the term "activated sludge"
- 1915 First full-scale activated sludge plant in Salford, England
  - 80,000 gpd at fill-and-draw operation (SBR)
  - 12,000 gpd at continuous-flow operation (Plug-flow)

Early History of Activated Sludge

- 1913 English patents by Jones and Attwood, Ltd
  - 25 cents/capita royalties paid by most WWTPs
- 1915 American patent by Leslie Frank (US Public Health officer)

Early History of Activated Sludge

- Walter Jones' U.S. activated sludge patent 1,947,540 was issued in 1917 and expired in 1934
- The last of the Jones' US patents expired in 1935



Early History of Activated Sludge

- 1915-1921 Ten full-scale plants in UK
- 1916-1927 Nine full scale plants in US
  - San Marcos, TX (1916)
  - Cleveland, OH (1916)
  - Houston (north), TX (1917)
  - Houston (south), TX (1918)
  - Des Plaines, IL (1922)
  - Calumet, In (1922)
  - Milwaukee, WI (1925)
  - Chicago IL and Indianapolis, IN (1927)

Early History of Activated Sludge

- Late 1920s – Patent infringement suits were filed by Activated Sludge, Ltd. (ASL), the licensed patentee for Jones and Attwood, Ltd. against US cities of Chicago, Milwaukee, Cleveland, and Indianapolis
- Lawsuits and threats of litigation led to:
  - Shutdown of several activated sludge plants in the US
  - Delays in designing activated sludge processes until ASL patents expired (e.g., 1935)/lawsuits exhausted (e.g., late 1940s)
- Both Chicago and Milwaukee paid large settlements (~$1.0 million each) to ASL in the 1940s

Early History of Activated Sludge

- Until 1995, U.S. patents were issued for a term of seventeen years, beginning on the issuance date
- Today, a patent's term still begins on the issuance date, but normally expires twenty years from filing date

Early History of Activated Sludge

- Most activated sludge development in the US was delayed until the 1950s due to:
  - Process royalties
  - Patent legalities
  - WWII
  - Example: Blue Plains – 1959

Activated Sludge

Process Description

Wastewater Treatment

- **Secondary (Biological) Treatment**
  - Purpose - BOD removal - Nitrification
  - Processes
    - **Activated sludge (suspended growth)**
    - Fixed film (attached growth)
    - Stabilization Ponds
  - Disposal of sludge and scum

Biological (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)

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 (Primary) alone can't provide
- **Activated Sludge** - a mixture of bacteria, fungi, protozoa (single cell), and metazoan (multi-cell) microorganisms maintained in suspension by aeration or mixing

Activated Sludge

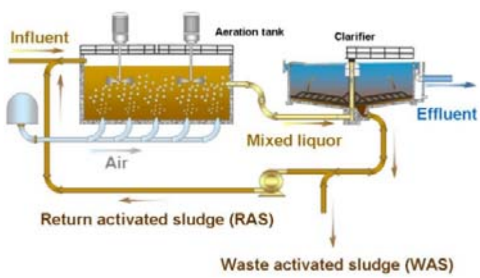
Activated Sludge Process

- Aeration and sedimentation tanks
- Oxygen – Air or pure oxygen
- Biomass – MLSS
- TSS, BOD, and TP Removal
- Nitrogen (BNR/ENR) removal
  - Nitrification (Oxic zones)
  - Denitrification (Anoxic zones)
- Need to waste solids to maintain target MCRT and F:M ratios
- Occasional foaming and bulking problems
- May need to add alkalinity in nitrification process

Activated Sludge Process Tanks

- **Aeration tank** – Tank where air (or oxygen) is injected in the mixed liquor.
- **Clarifier** - "Final clarifier" or "secondary settling tank" where biological floc (the sludge blanket) settles, separating biological sludge from treated water.

Activated Sludge Process



Activated Sludge Components

1. Mixing return sludge with wastewater forming a *mixed liquor*
2. *Aeration* and agitation of the mixed liquor (biomass - MLSS) 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

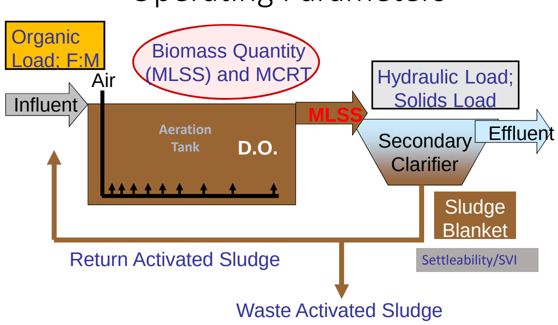
Return Activated Sludge

- 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

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.
- Typical wasting rates: 0.5 to 0.75 lbs/lb BODr

Operating Parameters



Activated Sludge

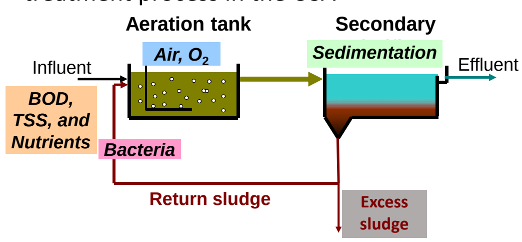
- Oxidizes carbonaceous matter (BOD)
- Nitrifies NH_3-N to NO_3-N
- MCRT/SRT:
  - > 1 day for BOD removal
  - > 7 days for nitrification (Temperature dependent)
- DO concentrations:
  - > 1.0 for BOD removal (Range: 1 – 2 mg/l)
  - > 2.0 for nitrification (Range: 2 – 4 mg/l)
- MLSS concentrations – 2000 to 8000 mg/l
- RAS – 50% of influent flow

Activated Sludge Environmental Factors

Parameter	Range
Food	Proper amount of food to microorganisms (F:M)
Hydraulic Flow Rate	Within plant design capacity. Excessive flows can result in suspended solids washout
Oxygen	Many of the bacteria in wastewater require between 1 mg/L to 3 mg/L of dissolved oxygen
Temperature	Most microorganisms in wastewater grow best between 10 and 25 degrees C. At >35 to 40 degrees C, thermophilic bacteria will take over
Nutrients	Conventionally a cBOD: Nitrogen: Phosphorus ratio of 100:5:1 is recommended in addition to proper micronutrients such as iron and other trace minerals
pH	Between 6.5-8.5 is recommended
Alkalinity	There needs to be enough buffering capacity to maintain pH. Typically 60 mg/L or more of alkalinity at the end of treatment is desired

Activated Sludge Process

- Today, the most widely used wastewater treatment process in the USA



Operating Parameters

- MLSS/MLVSS, mg/l
- Dissolved oxygen, mg/l
- pH and alkalinity

} Analytical data

- BOD, TSS, TN, and TP
- 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

Common Formulas for Activated Sludge

Organic Loading Rate: mg/L BOD (or COD) x flow, as MGD (millions of gallons per day) x 8.34

F/M Ratio: Lbs BOD per day/ lbs MLVSS (mixed liquor volatile suspended solids)

Retention time (hours): tank volume (MG) x 24 hours/ flow (MGD)

Solids Residence Time, SRT (days): lbs MLSS in system inventory/ lbs of suspended solids leaving the plant per day via wasting and as suspended solids in the effluent.

Removal percentage: This can be used to determine treatment rates for various parameters: lbs removed/ lbs in influent x 100

Loading Rates

- Organic loading rate – lbs BOD per day
  - Activated sludge - lbs BOD/day/1000 ft^3 of aeration tank
  - < 40 lbs BOD/day/1000 ft^3
  - Typical range: 15 to 25 lbs BOD/day/1000 ft^3
- Hydraulic loading rate – gpd/ft^2
  - Activated sludge clarifiers
  - Range: 300 to 1200 gpd/ft^2
- Solids loading rate – lbs TSS per day/ft^2
  - Activated sludge clarifiers
  - Range: 12 to 30 lbs TSS/day/ft^2

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).

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

Food-to-Microorganism Ratio

- Food to microorganism ratio (F:M or F/M) is the amount of food (BOD_5) 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

Flow and Hydraulic Retention Time

- The **hydraulic retention time** (**HRT**) is a measure of the average length of time wastewater remains in a tank, or time for wastewater **flow** to fill up a tank, or to completely replace the contents of a tank
- HRT = $V_t/\{Q_{in}/(24 \text{ hrs/day})\}$, hours
  Where: V_t is in MG
  Q_{in} is in MGD
- Typically, flow is in MGD, so flow must be converted to MG per hour:
  e.g., MGD/(24 hours/day)

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)

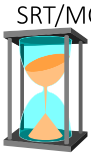
$$\frac{\text{Pounds of MLSS in aeration and clarifier tanks}}{\text{Pounds TSS wasted + Pounds TSS lost in eff.}}$$

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

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, w/o nitrification - 1 to 3 days
  - BOD removal and nitrification - 8 to 12 days

SRT/MCRT Calculations



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

Biomass in System, pounds / Pounds of solids leaving System per day

Biomass in System, pounds / Pounds TSS wasted + Pounds TSS lost in eff.

Process Control

- Three physical properties are monitored in wastewater:
  - Liquid flow: Wastewater, sludge quantities, chemical addition
  - Concentrations: MLSS, nutrients, sludge solids
  - Gases: air, digester gas

Common Controlled Variables

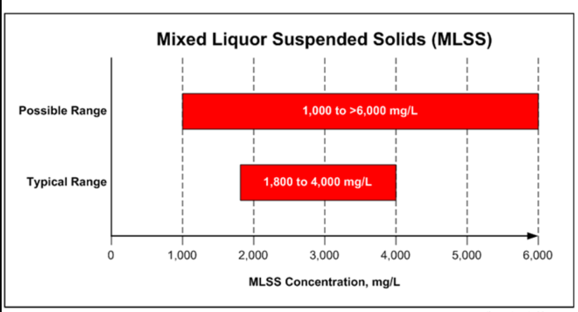
- Aeration
  - Set DO levels in different sections of process basin
  - Control aeration in time (cyclic aeration)
- Chemical Addition
  - Methanol, Ferric/Alum, Hypochlorite feed rates

Common Controlled Variables

- Internal Recycles
  - Set flow rates based on process conditions
- Sludge Wasting Rate
  - Control Solids Retention Time – One of the most important parameters for advanced BNR
- Others?
  - Creative thinking is key to advancement!

Activated Sludge Processes

Observations – Aeration Tank

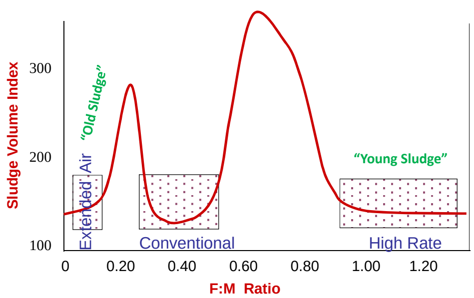


Aeration Tank Observations

- 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

Evolution of Act. Sludge Process 124

Process Variations and F/M Ratio



Evolution of Act. Sludge Process 125

Young Sludge

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

Evolution of Act. Sludge Process 126

Young Sludge

Poor Flocculation
Poor Settleability
Turbid Effluent

White
Billowing
Foam

High O_2
Uptake Rate

Old Sludge

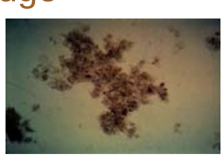
- Slow Metabolism
- Decreased Food Intake
- Low Cell Production
- Oxidation of Stored Food
- Endogenous Respiration
- Low F:M
- High CRT
- High MLSS

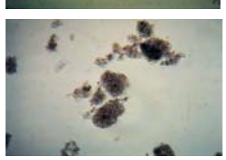
Old Sludge

Dense, Compact Floc

Fast Settling

Straggler Floc





Spray Wash for Foam Control

Activated Sludge Process

Aeration

Let's Focus on Oxygen

Aeration

Aeration

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

Aeration

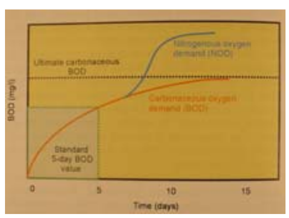
- Conventional activated sludge is an aerobic process. Many organisms in the activated sludge process need free oxygen (O_2) to convert food into energy for their growth.
- Typical Dissolved Oxygen (DO) concentrations:
  - Less than 1 mg/l - bulking potential
  - BOD removal - normal 1 to 2 mg/L
  - "Nitrification" - 2 to 4 mg/l

Aeration

- BOD Removal
- Nitrification – convert NH_3 to NO_3

Oxygen Requirements

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



Air Demand Requirements, lbs/day

Treatment	Equation	lb O_2/lb $_{oxidized}$
Organic Removal	$BOD_{oxidized} = BOD_{inf} - BOD_{eff}$	1.0 – 1.2
Nitrification	$TKN_{oxidizable} = TKN_{inf} - TKN_{assimilated}$ $TKN_{oxidized} = TKN_{oxidizable} - TKN_{eff}$	4.6

NPDES Effluent Requirement	OTR Equation
BOD5 Limit	1.2 * BODoxidized
BOD5 + NH3-N Limit	1.2 * BODoxidized + 4.6 * TKNoxidized

Aerobic Processes

- Aerobic processes require O_2 for removal of organics (BOD) and conversion of ammonia-N to Nitrate-N (nitrification)
- Oxygen can be supplied by air or 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

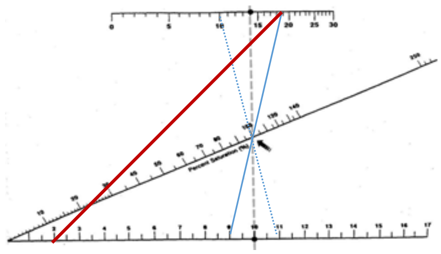
Mixing requirements

- 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

Importance of Dissolved Oxygen

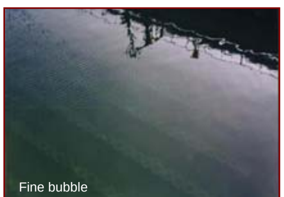
- Oxygen is sparingly soluble in water
- DO is a growth-limiting substrate
- C*ritical oxygen concentration* is about 10% to 50% of DO saturation in water
  - 10% minimum saturation (~ 1.0 mg/l DO) for BOD removal to less than 15 mg/L
  - 20% minimum saturation (~ 2.0 mg/l DO) for complete nitrification

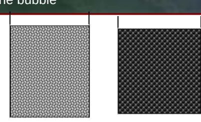
D.O. - Percent Saturation in Water



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

Gas transfer devices





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

Types of Air Blowers

- Multistage Centrifugal
- Positive Displacement
- Single Stage Centrifugal (integral gear)
- High Speed Direct Drive (turbo)

Evolution of Act. Sludge Process 145

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

Evolution of Act. Sludge Process 146

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

Evolution of Act. Sludge Process 147

Activated Sludge

Microbiology

Mixed Liquor Suspended Solids

- The concentration of suspended solids in an aeration tank is 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.

Microbial Ecology of Activated Sludge

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

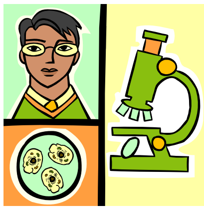
Microbial ecology of aerobic processes

- Remaining 5% of biomass consists of protozoans and metazoans
  - Presence of protozoans and metazoans indicates toxic free (e.g., NH_3) environment
  - Ciliated protozoan indicate good settling sludge
  - Free swimming protozoan indicates dispersed growth (poor settling)
  - A small fraction of biomass is multi-cellular metazoans

Activated Sludge

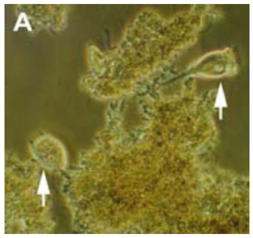
- Protozoa (single-cell organisms)
  - Amoeba
  - Flagellates
  - Free-swimming ciliates
  - Stalked ciliates
- Metazoans (multi-cell organisms)
  - Rotifers
  - Nematodes
  - Worms
  - "Water Bears"

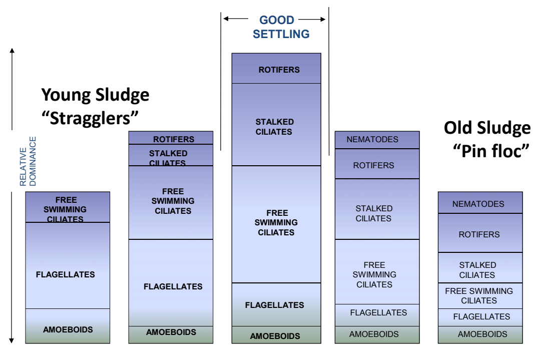
Microscope Exam



Floc Biology - Indicator of AS Health

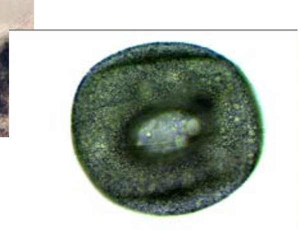
- The diversity and activity of organisms found in floc can indicate the health of the biological process.
- An abundance of protozoans such as rotifers indicates healthy situation





Relative Number of Microorganisms vs Sludge Quality

Amoeba



Amoeba

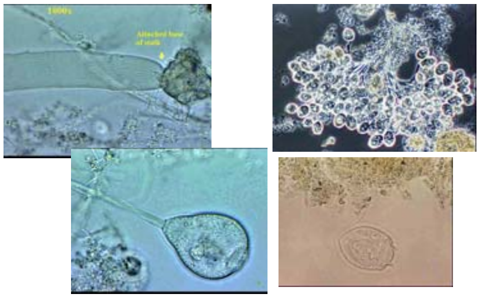
- Single-celled protozoans
- Indicative of "young" sludge
- Minimal contribution in WW treatment
- High concentration =
  - BOD shock loading
  - Presence of large amount of particulate matter
  - Lack of DO

Flagellate

Flagellates

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

Ciliates



Ciliates

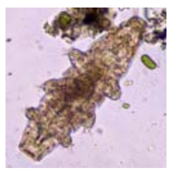
- Free-swimming
  - Peak after flagellates/ correspond to peak in bacteria concentrations
- Stalked
  - Peak after free-swimming
  - Good indicator of settleable sludge

Rotifers

Rotifers

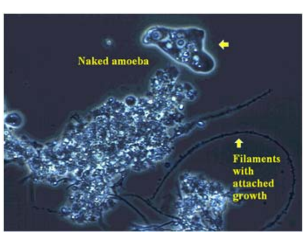
- Number very small
- Appear late in development of activated sludge
- Indicative of “old” sludge
- Sensitive to NH_3 levels, pH, temperature, etc.

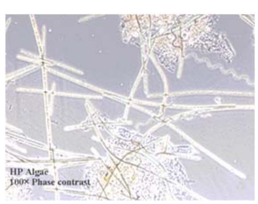
“Water Bears”



- *Tardigrade*
- Eight legs
- Can’t tolerate NH_3
- Presence in activated sludge biomass indicates absence of NH_3
- Feeds on other protozoa

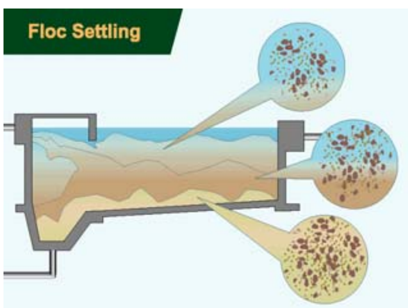
Filaments

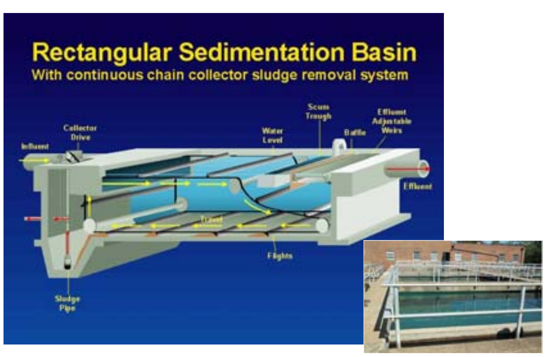




Activated Sludge Processes

Observations – Clarifiers





Circular Sedimentation Basin

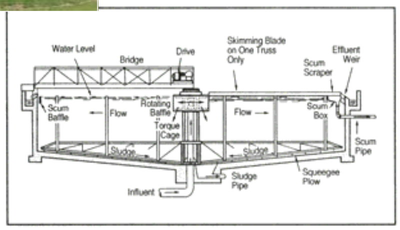
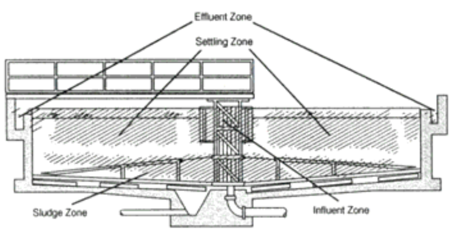


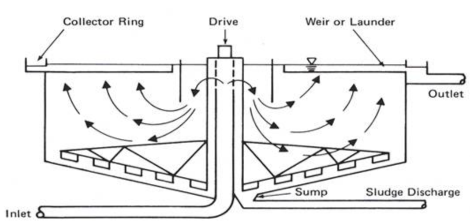
FIGURE 5-5 A typical circular sedimentation basin

Courtesy of FMC Corporation, MHS Division

Zones in a Sedimentation Basin



Circular Sedimentation Schematic



Center Feed Clarifier

Typical Operating Parameters — Secondary Clarifiers	
Parameter	**Operating Range**
Detention Time	2.0 to 3.0 hours
Weir Overflow Rate	5,000 to 15,000 gallons per day per lineal foot of weir
Surface Settling Rate or Surface Loading Rate	300 to 1,200 gallons per day per square foot of clarifier surface area
Solids Loading Rate	12 to 30 pounds of solids per day per square foot of clarifier surface area

Source: California State University, Sacramento. "Operation of Wastewater Treatment Plants." Volume 1, 4th ed. 1998.

thewastewaterblog.com

Circular Collectors

- Rotate Clockwise
  - Surface Skimmers for Grease
  - Bottom Flights for Settled Solids
- Solids Removal
  - Pump
  - Gravity
  - Draft Tubes

Effects of Water Temperature on Clarification

- Warm Water = Improved Clarification
- Cold Water = Reduced Clarification

Final Clarifier Capacity

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

Final Clarifier Operation

- Maintain final clarifier sludge blanket 1 to 2 feet; <30% of clarifier sidewall depth
- If blanket level rises, increase return sludge pumping rate.
- If there is no blanket, reduce return sludge pumping rate.

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

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.

Final Clarifier Observations

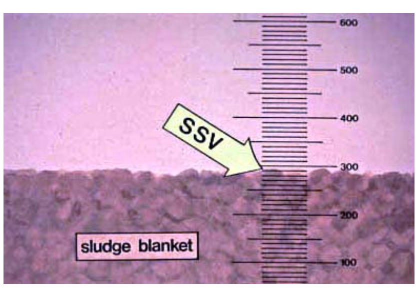
Settled Solids Observations

Settled Solids Observations

Side-by-Side Comparisons

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

Final Clarifier Observations



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.

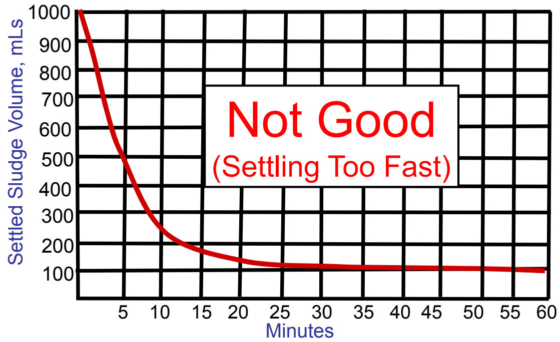
Mixed Liquor Settling Characteristics

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

- 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

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

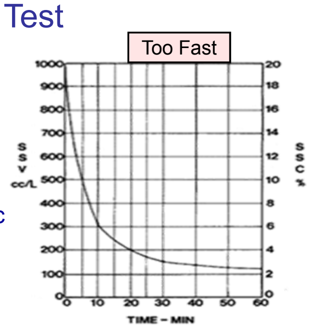
- SVI = 100 mL/g – considered good settling sludge
- SVI varies between 50-150 mL/g in properly operating diffused air activated sludge plant

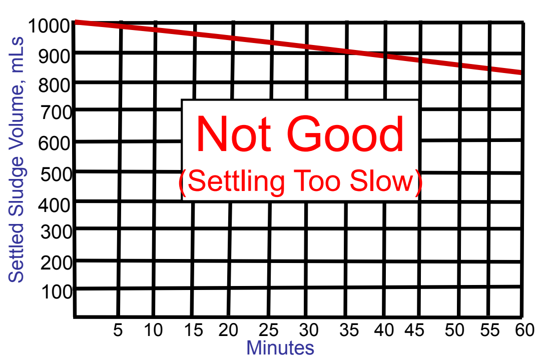


Settleometer Test

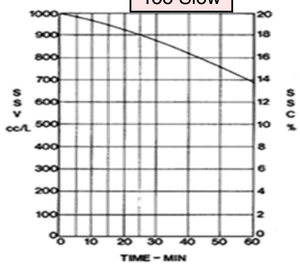
Indication of "Old" Sludge

Leaves Straggler Floc in Effluent





Settleometer Test



Not Compacting (Bulking)

Solids Washed Out in High Flows

Activated Sludge Process

Configurations

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

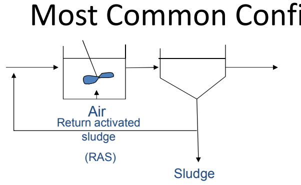
Activated Sludge - Extended Aeration

- 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

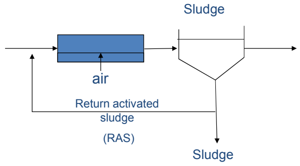
Activated Sludge - Extended Aeration

- 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

Most Common Configurations



Complete mix activated sludge process

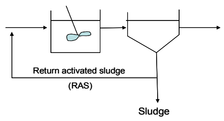


Plug Flow process

Conventional Activated Sludge

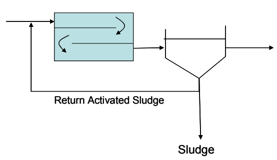
Complete Mix Activated Sludge

- Advantages:
  - 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 – uniform, low, limited S in reactor



Activated Sludge - Plug Flow

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



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.

Conventional Activated Sludge

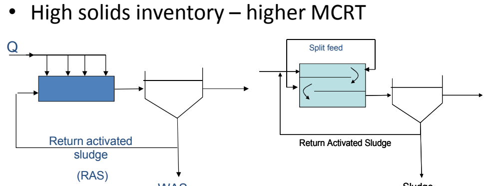
- **PLUG FLOW -** Long narrow tank, or a series of several long tanks
- Primary effluent and return activated sludge (RAS) combined at influent of aeration tank
- Dissolved oxygen (DO) demand is highest at the aeration tank entrance; more air (oxygen) is required
- As BOD is depleted, process may successfully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

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

Step Feed Activated Sludge

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

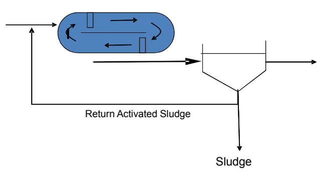


Step Feed Activated Sludge

- Advantages of Step-Feed Configuration:
  - Equalize Food/Mass ratio across basin
  - 3 to 5 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

Oxidation Ditch

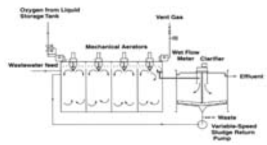
- Unidirectional channel flow
- 0.5-1.0 ft/sec velocity keeps sludge in suspension
- Long HRT (24 hrs), long MCRT (>30 days)



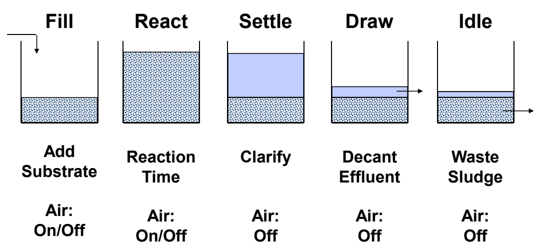
Oxidation Ditch

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

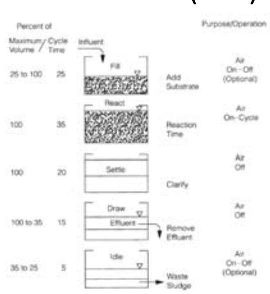


Sequencing Batch Reactor



Sequencing Batch Reactor (SBR)

- One Tank Process
- No Secondary Clarifiers
- Cycles:
  - Fill
  - Aeration
  - Settle
  - Withdrawal
  - Idle



Activated Sludge Process

BOD Removal to Nitrification

Forms of Nitrogen

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

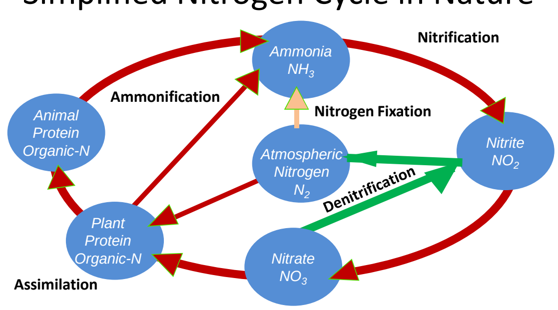
TKN (Un-oxidized) — Ammonia(um), Organic Nitrogen

NO_x (Oxidized) — Nitrite, Nitrate

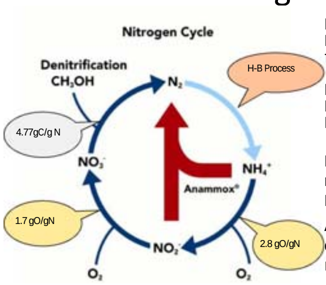
Total Nitrogen (TN) = TKN + NO_x

TKN = Total Kjeldahl Nitrogen

Simplified Nitrogen Cycle in Nature



The Nitrogen Cycle



H-B process:
Haber-Bosch nitrogen fixing (chemical) process

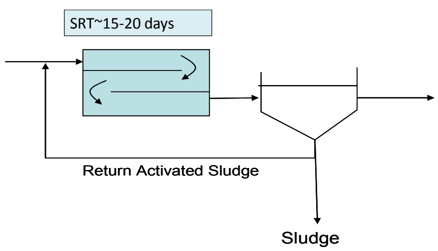
N/DN Uses O_2 for Nitrification, Carbon for Denitrification

N/DN can be reduced if not going all the way to Nitrate

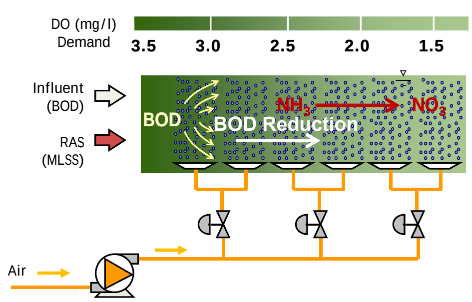
Anammox bacteria can eliminate carbon while reducing oxygen to 60%

Nitrification by slow growing temperature sensitive autotrophs

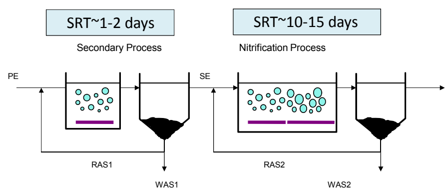
Extended Aeration for BOD Removal and Nitrification



BOD Removal and Nitrification



Two Sludge System for BOD Removal and Nitrification (1970s)

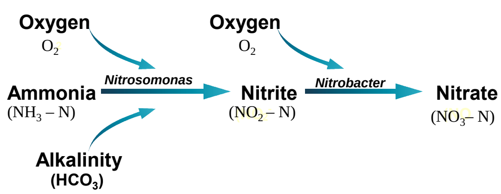


Blue Plains, DC Water 370 MGD

Western Branch, WSSC 30 MGD

Nitrification

- For 125 years, nitrification was believed to be solely a two-step process:

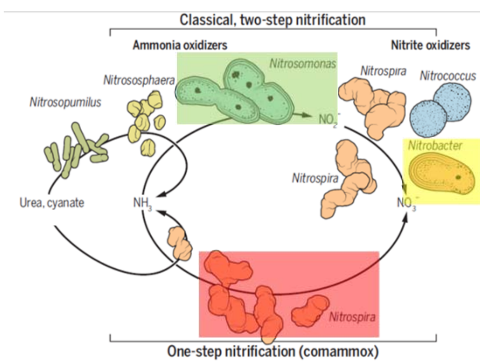


Nitrification

- Two-step nitrification depends on two organisms, which was the basis for hundreds of studies on nitrification in wastewater treatment
- A single microbe capable of catalyzing both nitrification steps may actually conserve energy

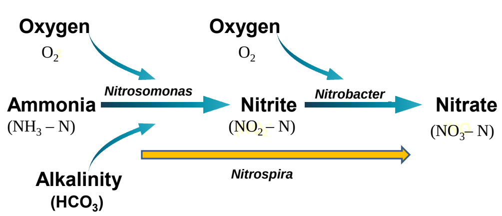
Nitrification - Comammox

- **Comammox** (COMplete AMMonia Oxidixer) is the name for a single organism that can convert ammonia into nitrite then nitrate
- Existence of comammox organisms were first predicted in 2006
- In 2015, the presence of such organisms was confirmed within *Nitrospira*
- The Nitrogen cycle has since been updated

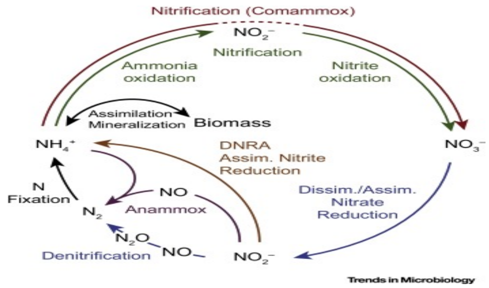


Nitrification

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



Nitrogen Cycle in Wastewater (2016)



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.

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

Nitrification Problems

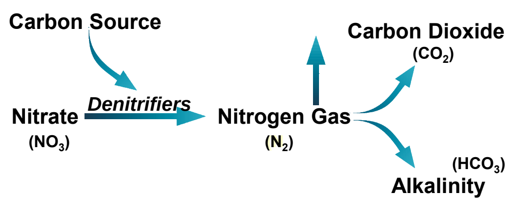
Possible Causes	Solution
Insufficient MCRT	Increase MCRT to establish nitrification by reducing sludge wasting
Insufficient DO in aerobic zone (~ 2.0 mg/L goal)	Increase aeration by adjusting air valves, increasing blower output, or turning on another blower.
Insufficient alkalinity	Add supplemental 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

Activated Sludge Process

Denitrification

Denitrification

Reduction of nitrates or nitrites commonly by bacteria usually resulting in the escape of nitrogen in the air.



Denitrification Requirements

- Nitrification to produce nitrite/nitrate
- Anoxic zones with low/no DO
  - Baffling and zone segregation
  - Minimize DO carryover from aerated zones
- Readily biodegradable carbon (rbCOD)
  - Raw Influent BOD (~ 5-6 lbs BOD/lb NO3-N denitrified)

Evolution of Act. Sludge Process 79

Denitrification Requirements

- Impact on Oxygen and Alkalinity:
  - Alkalinity is *produced* in Denitrification
    - 50% of alkalinity consumed in Nitrification is recovered in denitrification
- Nitrification:
  - $NH_4+ + 2\ O_2 \rightarrow NO_3^- + 2H^+ + H_2O$
- Denitrification:
  - $6NO_3^- + 5CH_3OH \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^-$

Evolution of Act. Sludge Process 80

Conditions in the Anoxic Zone

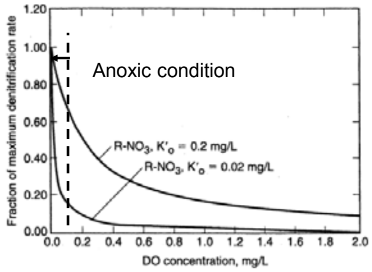
DO less than 0.1 mg/l
- **No aeration**
- **Low aeration**
- **Cyclical Aeration**

Carbon source
- **Primary Effluent**
- **Endogenous**
- **Methanol**

Mixing
- **Submersible mixers**
- **Vertical mixers**

Evolution of Act. Sludge Process 81

Reduction in rate of Denite as a function of D.O.
(K'o is oxygen inhibition constant)



Inhibition of Denite Process

- Environmental Conditions
  - pH
  - Temperature
  - **Aerobic Conditions!** Keep DO< 0.2 mg/L
- Insufficient amount of rbCOD (Carbon Substrate).
- Presence of Chemical Inhibitors:
  - Substrates, intermediates, and products of denitrification
  - Synthetic organic chemicals
  - Heavy metals - Hg, Ni, Pb, etc.

Denitrification

Note: (Almost) all nitrates returned to the anoxic zones should be denitrified

The "goal" NO_3-N concentration in the effluent from the last anoxic zone should be between 0 and 0.5 mg/L.

Carbon for Denitrification

- Influent WW Carbon
  - Utilized in first anoxic zone
  - EBPR can compete for carbon
  - Limited carbon available for secondary anoxic zones – and effective denite
- Endogenous Carbon
  - Slow kinetics – limited denite in post-anoxic zones
- Supplemental Carbon
  - Methanol typically used
    - But requires methylotrophic population!
  - Alternatives to methanol – ethanol, acetic acid, glycerin, sugars, mono-propylene glycol, proprietary products

Other Carbon Sources

- Alcohols
  - Methanol
  - Ethanol
- Glycerol/glycerin – (Biodiesel by-products)
- Acetates - (Acetic acid, sodium acetate)
- Carbohydrates - (Sucrose, sugar water, corn syrup)
- MicroC™ – (Carbohydrate, glycerin, alcohol based blends)

Carbon for Denitrification

- If using methanol – may not have adequate methylotrophic population
  - Need well controlled anoxic volume
  - Methylotrophs may require acclimation time
  - Methylotrophs are believed to be more sensitive to temperature
- Methanol is typically more sensitive to pH and may not be effective in very cold weather
  - Change carbon source – ethanol or glycerin
- Denitrification batch tests
  - Specific denitrification rates (SDNRs) – different carbon sources

Inhibition by specific Chemicals

- Strong Inhibitors
  - Acetylene (C_2H_2)
  - Sulfide (S^{2-})
  - Chlorate (ClO_3^-)
  - Heavy metals
  - Cyanide (CN^-) and Azide (N_3^-)

Denitrification Problems

Possible Causes	Solution
Not enough nitrates being returned to anoxic zone	Increase nitrate recycle pump speed
Not enough BOD entering anoxic zone	- Bypass primary clarifiers, or - Add supplemental carbon (for example, methanol) to anoxic zone
BOD entering the anoxic zone breaks down too slowly	Add readily available carbon source such as methanol to anoxic zone or increase the anoxic zone hydraulic retention time
High DO in the anoxic zone	Try to limit backmixing of air from the aerobic zones or decreasing the DO in the AT influent. Decrease nitrate recycle rate if necessary.

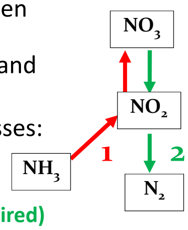
Activated Sludge Process

Nitrification to BNR

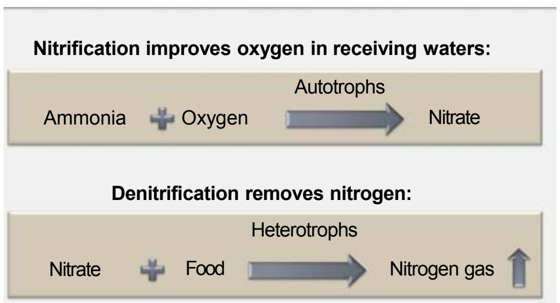
Nitrogen Removal - Basics

Nitrification + **Denitrification** = Nitrogen Removal

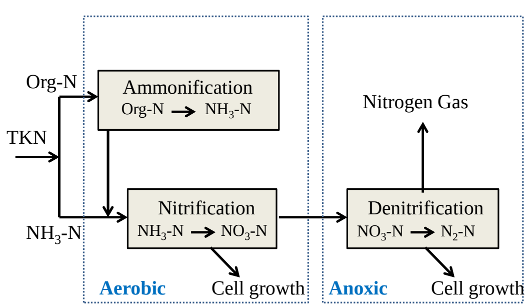
- BNR/ENR converts TKN nitrogen (primarily ammonia) in wastewater to nitrite/nitrate and ultimately ***nitrogen gas***
- BNR/ENR requires two processes:
  - **1: Nitrification (O_2 & HCO_3 required)**
  - **2: Denitrification (Carbon required)**



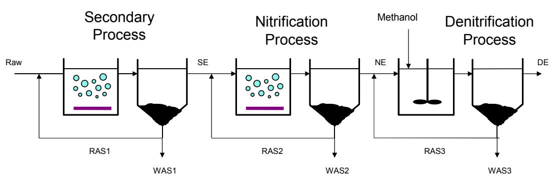
Nitrification-Denitrification



Nitrification-Denitrification

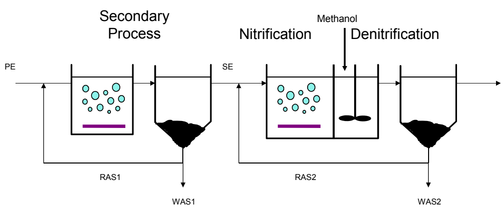


Three Stage System for BOD Removal and Nitrogen Removal to <3 mg/L



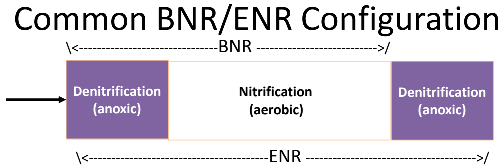
Western Branch WWTP, WSSC 30 MGD (late 1980s)

Two Sludge System for BOD Removal and Nitrogen Removal to <5 mg/L



Blue Plains, DC Water 370 MGD (beginning early 1990s)

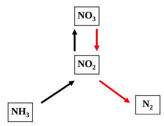
Common BNR/ENR Configurations

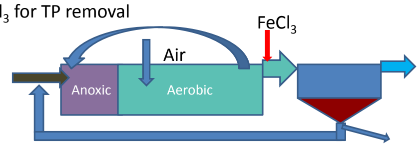


- BNR:
  - Modified Ludzack-Ettinger (MLE)
  - Anaerobic/Anoxic/Oxic (A2O)
  - University of Cape Town Process (UCT)
- ENR:
  - Enhanced MLE/4-stage Bardenpho
  - MLE with Denitrification Filter

Nutrient Removal

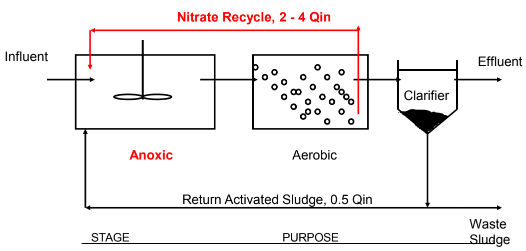
- Nitrification (*Nitrosomonas* and *Nitrobacter*)
  $NH_3 + O_2 \rightarrow NO_2^- \rightarrow NO_3^-$
- Denitrification
  $NO_3^- + \text{organics} \rightarrow CO_2 + N_2$
- BNR Process – MLE
- $FeCl_3$ for TP removal





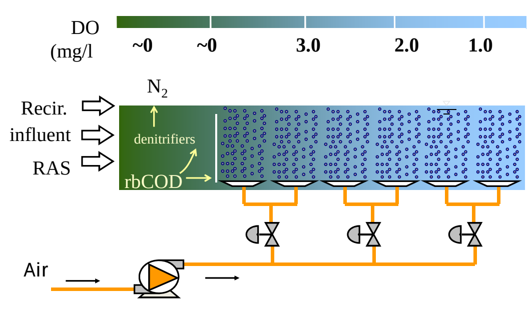
Modified Ludzack-Ettinger BNR Process

Denitrification-Nitrification with Nitrate Recycle

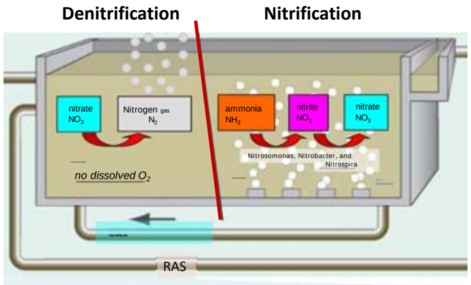


STAGE	PURPOSE
Anoxic	BOD Removal, Denitrification, and Nitrogen gas release
Aerobic (Oxic)	Nitrification zone

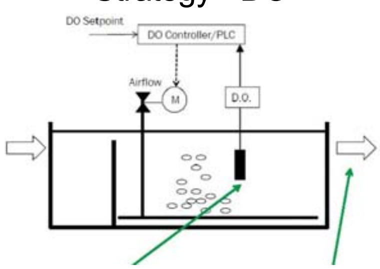
Denitrification/Nitrification Layout



Biological Nitrogen Removal



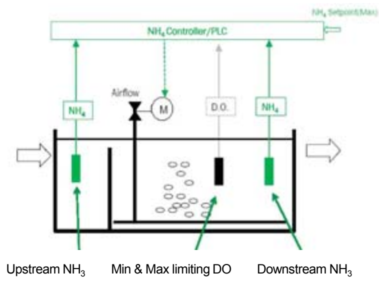
Typical Aeration Basin Control Strategy - DO



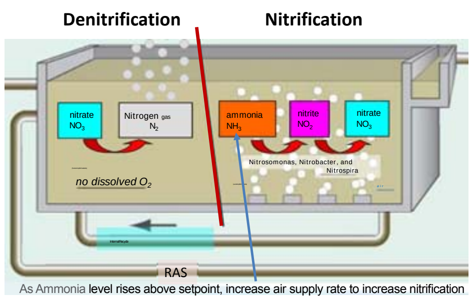
Objective of Ammonia based Aeration control

- Aeration is limited to:
  - Prevent complete nitrification
  - Reduce effluent ammonia peaks
- Potential benefits include:
  - Decreased energy expenses (for aeration)
  - Possibly increased denitrification with less supplemental carbon addition
  - Possibly improved Bio-P removal

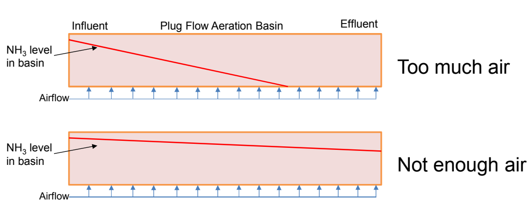
Ammonia Feed Forward – Feedback Control



Biological Nitrogen Removal

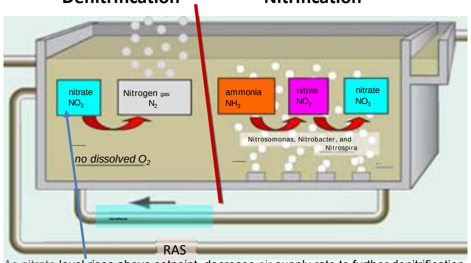


Ammonia-Based DO Control



Biological Nitrogen Removal

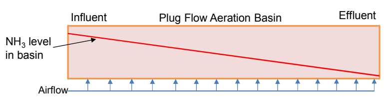
Denitrification **Nitrification**



As nitrate level rises above setpoint, decrease air supply rate to further denitrification

Ammonia-Based DO Control

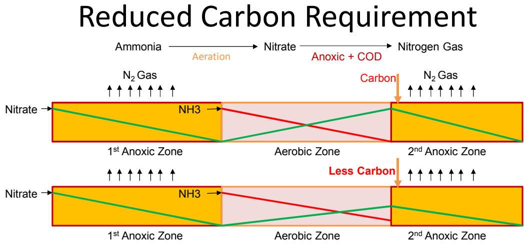
- Operator selects effluent ammonia setpoint
  - Complete nitrification, NH_3-N ~ 0.1 mg/L
  - Incomplete nitrification, NH_3-N ≤ 1.0 to 2.0 mg/L



Just right

- When effluent ammonia is greater than setpoint, controller increases DO
- When effluent ammonia is below setpoint, controller decreases DO

Benefit of Ammonia-Based DO Control
Reduced Carbon Requirement

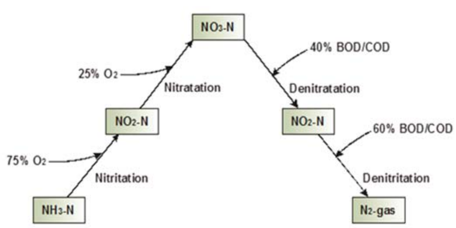


Advanced (Tertiary) Treatment

- Nutrient Removal with Activated Sludge
  - Total Nitrogen (TN) removal
    - Nitrification
    - Denitrification
    - BNR and ENR technologies
      - EPA Model (Nitrification/Denitrification)
      - Modified Ludzack-Ettinger – MLE (Denitrification/Nitrification)
      - Enhanced MLE/Bardenpho – MLE with post denitrification

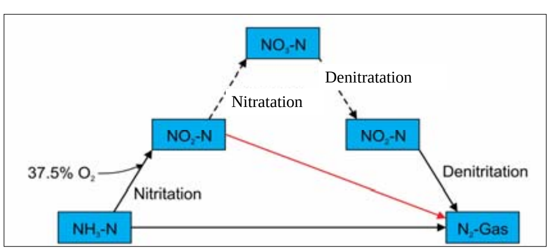
Simultaneous Nitrification and Denitrification (SNDN)

Traditional pathway of biological nitrogen removal

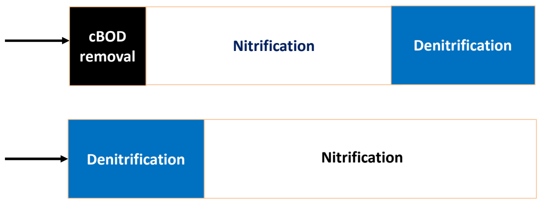


Deammonification

"ANAMMOX"



Typical Biological N Removal Configurations



Nitrification-Denitrification ENR Configurations

- Specific WWTPs:
  - Blue Plains (DC)
  - Western Branch (WSSC)
  - Patapsco (Baltimore)
- Sequencing Batch Reactors

Biological Nutrient Removal (BNR)

- BNR converts/removes Nitrogen (primarily ammonia – NH_3) in wastewater to nitrite (NO_2), nitrate (NO_3), and ultimately to nitrogen gas (N_2).
- BNR is a two step process:

  Step 1: Nitrification

  Step 2: Denitrification

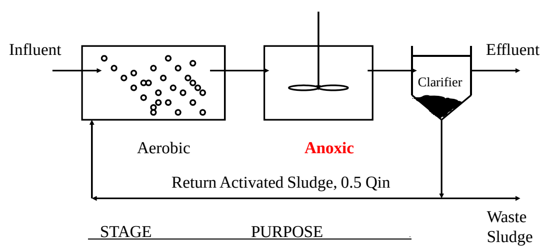
Milestones

- 1954 Wuhrman proposes 2-stage, aerobic - anoxic process
- 1957 Davidson proposes 2-stage, anaerobic - aerobic Process
- 1962 Ludzack and Ettinger propose 2-stage, anoxic – aerobic process
- 1967 Leven patents Phostrip®, a sidestream phosphorus removal process

Milestones

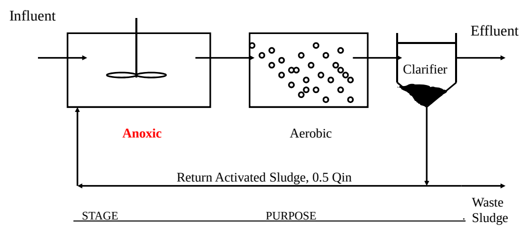
- 1968 Barth proposes 3-sludge, activated sludge process for nutrient removal
- 1970 Savage patents denitrification filter
- 1973 Barnard in South Africa develops the Modified Ludzack-Ettinger process, which becomes the standard for the wastewater industry

Two Stage Wuhrmann BNR Process



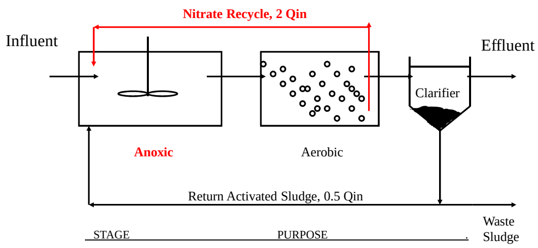
STAGE	PURPOSE
Aerobic (Oxic)	Nitrification
Anoxic	Denitrification and Nitrogen gas release

Two Stage Ludzack-Ettinger BNR Process



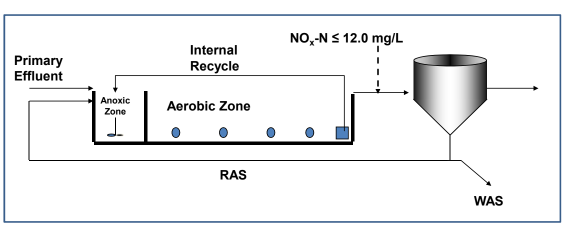
STAGE	PURPOSE
Anoxic	BOD Removal, Denitrification, and Nitrogen gas release zone
Aerobic (Oxic)	Nitrification zone

Modified Ludzack-Ettinger BNR Process



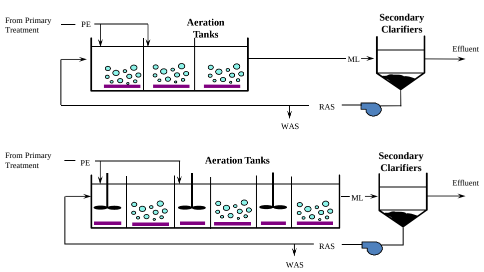
STAGE	PURPOSE
Anoxic	BOD Removal, Denitrification, and Nitrogen gas release
Aerobic (Oxic)	Nitrification zone

Modified Ludzack-Ettinger (MLE) Configuration

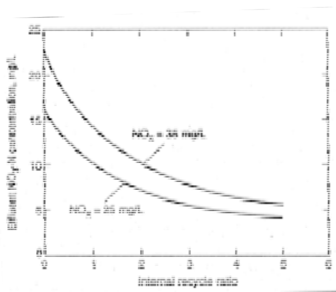


Modified Ludzack-Ettinger - MLE

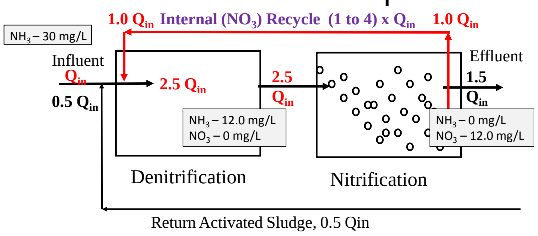
Step Feed Process



Impact of Internal Recycle on BNR Effluent TN

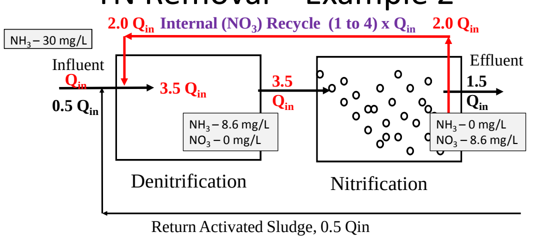


TN Removal – Example 1



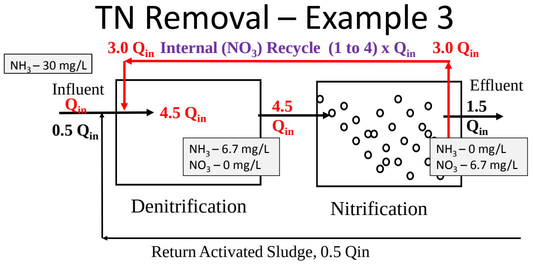
Assume all NO_3–N returned to Denitrification is converted to N_2
Assume all NH_3-N is converted to NO_3-N in Nitrification.
What is the NH_3-N concentration in Denitrification? $NH_3\text{-N} = \frac{30 \text{ mg/L}}{2.5/1} = 12.0 \text{ mg/l}$

TN Removal – Example 2



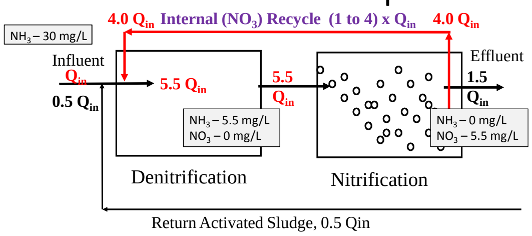
Assume all NO_3-N returned to Denitrification is converted to N_2
Assume all NH_3-N is converted to NO_3-N in Nitrification.
What is the NH_3-N concentration in Denitrification? $NH_3\text{-N} = \frac{30 \text{ mg/L}}{3.5/1} = 8.6 \text{ mg/l}$

TN Removal – Example 3



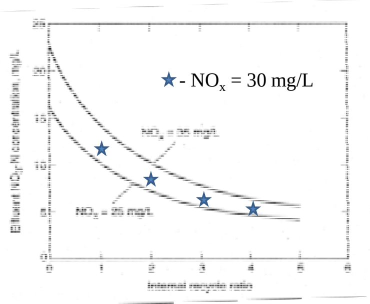
Assume all NO_3-N returned to Denitrification is converted to N_2
Assume all NH_3-N is converted to NO_3-N in Nitrification.
What is the NH_3-N concentration in Denitrification? $NH_3\text{-N} = \frac{30 \text{ mg/L}}{4.5/1} = 6.7 \text{ mg/l}$

TN Removal – Example 4

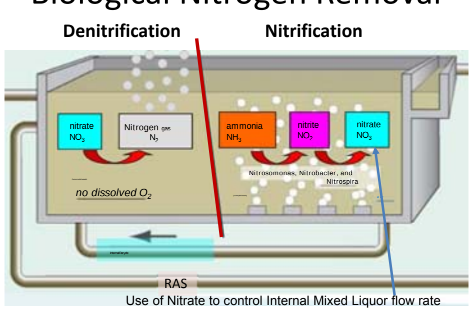


Assume all NO_3-N returned to Denitrification is converted to N_2
Assume all NH_3-N is converted to NO_3-N in Nitrification.
What is the NH_3-N concentration in Denitrification? $NH_3\text{-N} = \frac{30\ \text{mg/L}}{5.5/1} = 5.5$ mg/l

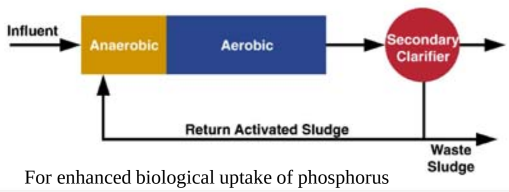
Impact of Internal Recycle on BNR Effluent TN



Biological Nitrogen Removal

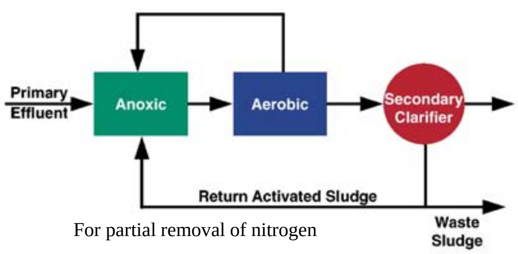


AO



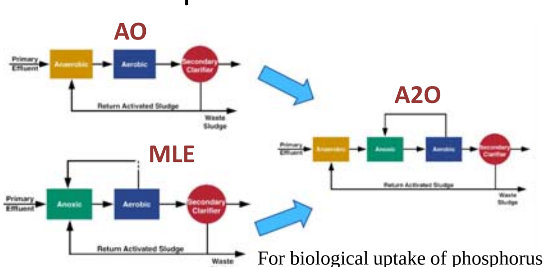
For enhanced biological uptake of phosphorus

Modified Ludzack-Ettinger - MLE



For partial removal of nitrogen

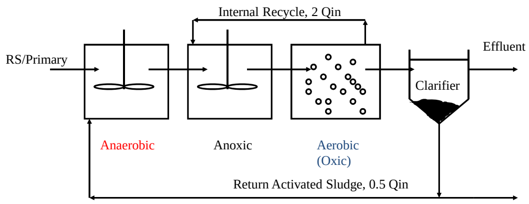
AO plus MLE = A2O



For biological uptake of phosphorus and partial removal of nitrogen

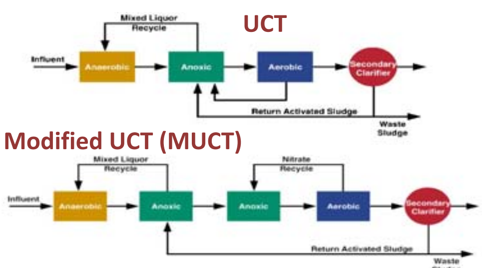
A20 Process

with Anaerobic Zone for Phosphorus Release



STAGE	PURPOSE .
Anaerobic	Soluble BOD uptake and phosphorus "release" zone.
Anoxic	Denitrification and nitrogen gas release zone
Aerobic (Oxic)	Nitrification and phosphorus "uptake" zone

UCT Processes



For biological uptake of phosphorus and partial removal of nitrogen

Historical View of BNR

- Recent efforts for nutrient removal for WWTPs with limited space for expansion has lead to:
  - Sequencing Biological Reactors (SBRs)
  - Membrane reactors
  - Side-stream treatment for phosphorus removal:
    - Struvite precipitation
  - Side-stream treatment for ammonia removal:
    - Deammonification with ANAMMOX

BNR Processes

Process	Nitrogen	Phosphorus	Comments
MLE	Good	None	- Moderate basin volume
Step Feed	Good	None	- No nitrate recycle
SBR	Moderate	Inconsistent	- No nitrate recycle
A2O	Good	Good	- Moderate basin volume - Sensitive to DO in return
Oxidation Ditch	Excellent	Good	-Long HRT and SRT - Tight DO controls necessary

High DO in the Anoxic Zones

- High DO in the anoxic zones may be more of a problem during the winter because more DO can be absorbed by colder water and biological kinetics are reduced.
- Lower the nitrate recycle rate in the winter if necessary

Denitrification

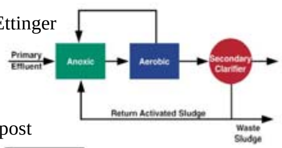
- **If effluent nitrate-nitrogen is above the goal:**
  - Verify nitrate recycle pumps are running.
  - Check nitrate recycle pump speed.
  - Verify very low DO in the anoxic zones.
  - Consider if low influent BOD or slowly degradable influent BOD could be inhibiting the process.

Activated Sludge Process

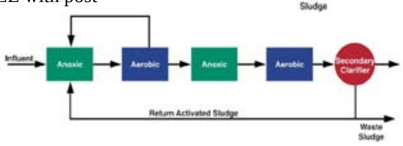
BNR to ENR

Example of BNR to ENR

Modified Ludzack Ettinger - MLE



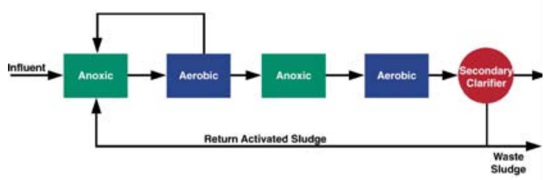
Enhanced MLE with post anoxic zone



Milestones

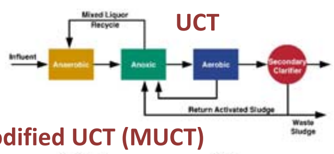
- 1975 Barnard patents Bardenpho® process
- 1976 Specter patents AO® and A2O® processes
- 1977 Jervis develops fluidized bed denitrification reactor
- 1980 University of Cape Town (UCT) process developed

Bardenpho
(Enhanced Modified Ludzack Ettinger)

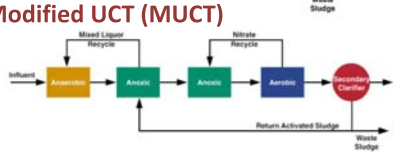


UCT Processes

UCT



Modified UCT (MUCT)



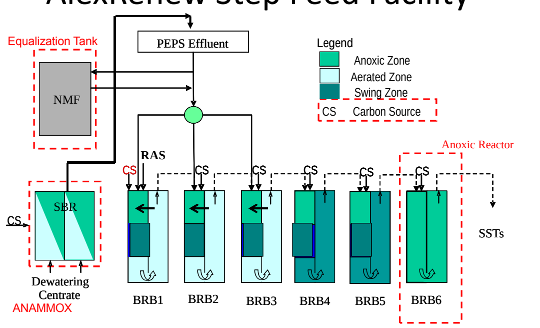
Anoxic Zone

- In the MUCT process, baffling or separate tanks are set up in the anoxic reactor.
  - First reactor (primary) receives underflow from settling tank
  - MLSS from first reactor is recycled to the anaerobic tank
  - Second anoxic reactor receives mixed liquor from aerobic tank

Enhanced Nutrient Removal (ENR)

- For WWTPs to upgrade from BNR to ENR, and satisfy new LOT requirements for nitrogen removal, an additional post-denitrification stage is required; for example:
  - MLE + post anoxic
  - MLE + Denit Filter
  - Step feed + post anoxic
  - Step feed + Denit Filter

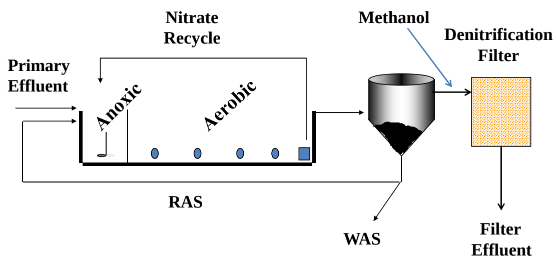
AlexRenew Step Feed Facility



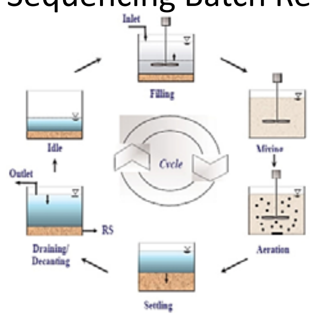
ENR Processes

Process	Nitrogen	Phosphorus	Comments
Enhanced MLE (Bardenpho)	Excellent	None	- Large basin volume - Need for methanol
Modified UCT	Good	Excellent	-Separate anoxic zone for RAS - Several nitrate recycle streams - Increased complexity
5-stage Bardenpho	Excellent	Good	- Larger reactor volume - Need for methanol
Oxidation Ditch	Excellent	Good	-Long HRT and SRT - Tight DO controls necessary

MLE With Denitrification Filter



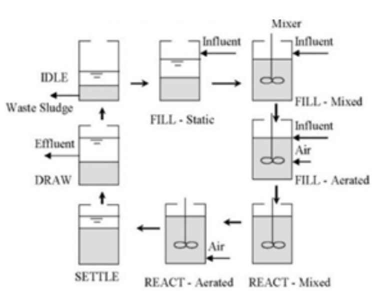
Sequencing Batch Reactor



Denitrification

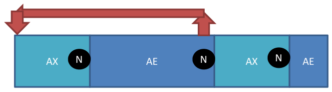
Nitrification

Sequencing Batch Reactor



Nutrient-Paced Mode is Most Accurate

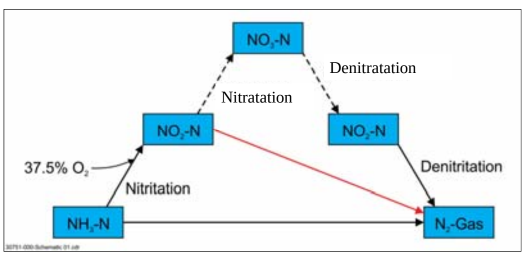
- Requires nitrate probes/analyzers
  - Locate in/out of anoxic zone and filters
- Operator input
  - Effluent nitrate setpoint (mg/L)



Typical probe locations

Nitritation/Deammonification

"ANAMMOX"



SBR-type Anammox Process

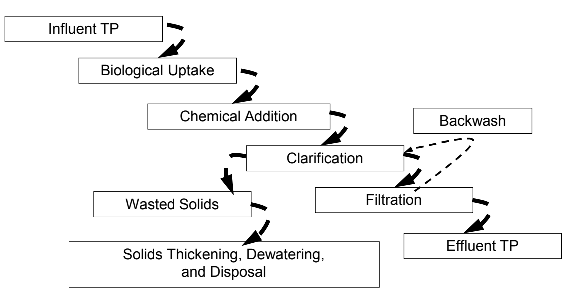
- Three 8-hour Cycles per day using special bacteria
- Hampton Roads and Alexandria, Virginia

Advantages and Disadvantages of BNR/ENR

- Advantages
  - No chemicals
  - No additional chemical sludge
  - retrofits well with any activated sludge process
  - Additional benefit of nitrogen removal
- Disadvantages
  - Except for Phostrip, phosphorus removal is a function of BOD:TP ratio
  - Not easily retrofitted to fixed film facilities
  - Standby chemical addition may be necessary as a backup

Phosphorus Removal Processes

Phosphorus Removal



Phosphorus Removal - Basics

1. **Chemical precipitation** – two mechanisms:
   - **Co-Precipitation** (Remove TP ~ 0.5 mg/l)
     - $\underline{2}Al + 3OH + PO_4 \text{ ----> } \underline{2}Al(OH)_3PO_4 \downarrow$
   - **Adsorption** (Remove TP < 0.5 mg/l)
     - $x\,(Al + 3OH) \text{ ---> } x\,(AlOH_3) \downarrow$
     - $x\,(AlOH_3)\downarrow + PO_4 \text{ ----> } x\,(Al(OH)_3) \cdot PO_4 \downarrow$
     - $x > 2$; more chemical required as PO_4 levels drop
   - Both reactions form Metal-Hydroxide-Phosphate sludge
2. **Biological Uptake**
   - Conventional/background uptake (2 to 3%)
   - Luxury/excess uptake (BNR/ENR - 3 to 6%)

Phosphorus Removal Options

- Source control – bans on phosphates in detergents
- Physical removal of particulate phosphorus during sedimentation and filtration
- Biological uptake
- Chemical addition with alum or $FeCl_3$

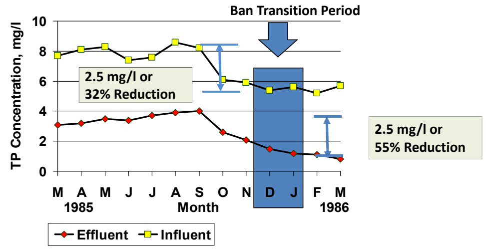
Phosphate Bans in Detergents

In the mid-1980's, Maryland, Pennsylvania, Virginia, and the District of Columbia instituted bans on phosphates in laundry detergents.

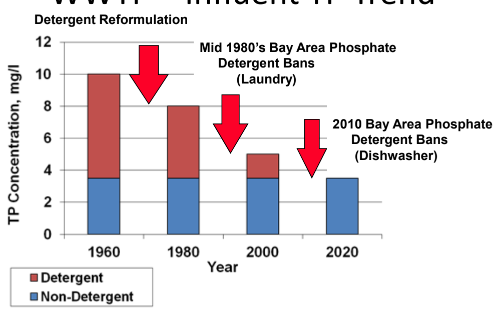
Nearly 25 years later, a second regional ban became effective on phosphates in automatic dishwasher detergents.

Reduction in Phosphorus after Phosphate Ban - 1985

(2.5 mg/l P Drop @ WSSC's Western Branch WWTP)



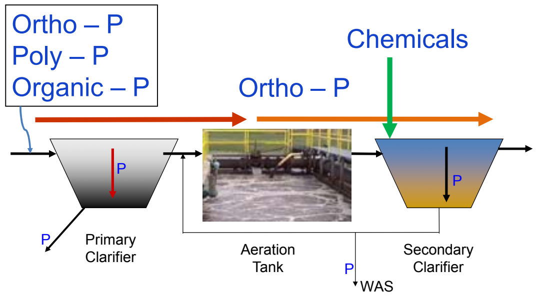
WWTP – Influent TP Trend



Background Uptake

- Conventional Biological Uptake
  - To satisfy biological needs
- Excess Biological uptake
  - Stress induced
  - Anaerobic zones
  - Release of phosphorus under anaerobic conditions
  - Uptake of phosphorus under aerobic conditions

Phosphorus Removal

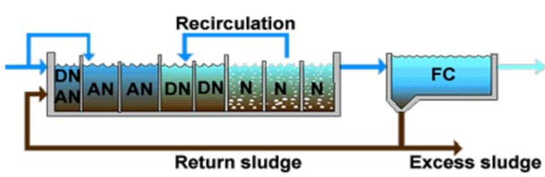


Biological Phosphorus Removal Concept

- Modify treatment system so that waste activated sludge contains higher than normal concentrations of phosphorus.
- 2 to 3 times as much phosphorus removed in BNR Systems
  - Conventional - 1 to 3%
  - BNR Systems - 2 to 6%

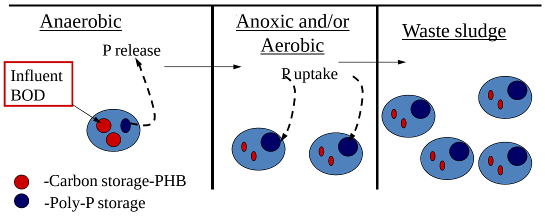
A2O

(Anaerobic/Anoxic/Oxic)

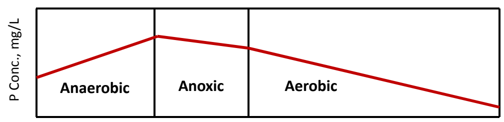


Biological TP Uptake

P is removed by phosphorus accumulating organisms (PAOs) and exits system in waste sludge



Phosphorus Profile – A2O



Anaerobic zone
P - Release

Anoxic and Aerobic zones
P - Uptake

Phosphorus Removal with Chemicals

Chemical precipitation – two mechanisms:

- **Co-Precipitation** (Remove TP ~ 0.5 mg/l)
  - $\underline{2}Al + 3OH + PO_4$ ----> $\underline{2}Al(OH)_3PO_4 \downarrow$
- **Adsorption** (Remove TP < 0.5 mg/l)
  - $x\,(Al + 3OH)$ ---> $x\,(AlOH_3) \downarrow$
  - $x\,(AlOH_3) \downarrow + PO_4$ ----> $x\,(Al(OH)_3)\cdot PO_4 \downarrow$
  - $x > 2$; more chemical required as PO_4 levels drop
- Both reactions form Metal (Al or Fe)-Phosphate-Hydroxide sludge

Simplified Iron Reactions

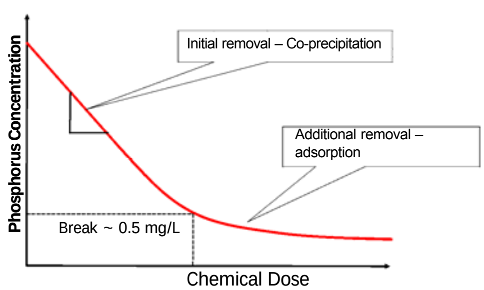
- $FeCl_3 + PO_4^{-3}$ ---> $FePO_4 + 3Cl^{-1}$
- $FeCl_3 + 3HCO_3^{-1}$ ----> $Fe(OH)_3 + 3CO_2 + 3Cl^{-1}$

- Simplified: Fe + PO_4 ------> $FePO_4$
  Fe + 3OH ------> $Fe(OH)_3$
- Combined:
  2Fe + PO_4 + 3OH ----> $2FePO_4(OH)_3$ Complex ↓
  (Mole Ratio = 2.0)

Simplified Aluminum Reactions

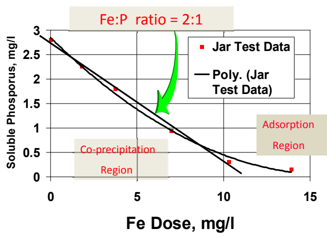
- $Al_2(SO_4)_3 \cdot 14H_20 + 2PO_4^{-3}$ ------> $2AlPO_4 + 3SO_4^{-2} + 14\ H_2O$
- $Al_2(SO_4)_3 \cdot 14H_20 + 6HCO_3^{-1}$ ------> $2Al(OH)_3 + 6CO_2 + 14\ H_2$

- Simplified: Al + PO_4 ------> $AlPO_4$
  Al + 3OH ------> $Al(OH)_3$
- Combined:
  2Al + PO_4 + 3OH ----> $2AlPO_4(OH)_3$ Complex ↓
  (Mole Ratio = 2.0)



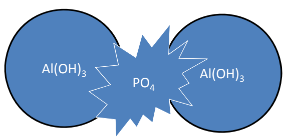
Phosphorus Removed with $FeCl_3$

Blue Plains - June 1977



Co-precipitation Model

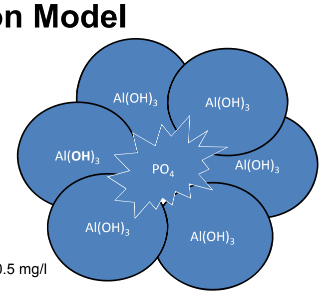
$2Al + PO_4 + 3OH$ ----> $2AlPO_4(OH)\downarrow$



$2AlPO_4(OH)_3$ Complex ↓

- ✓ For PO_4 concentrations > 0.5 mg/l
- ✓ Stoichiometric chemical reactions
- ✓ Mole ratio – 1.5 to 2.0

Adsorption Model



- ✓ For PO_4 concentrations < 0.5 mg/l
- ✓ More chemical needed
- ✓ Mole ratio – 2.0 to 10.0

Typical Chemicals Used To Precipitate Phosphorus

- Alum - $Al_2(SO_4)_3{\cdot}14H_20$
- Ferric Chloride - $FeCl_3$
- Poly-Aluminum Chloride (PACl)
- Pickle Liquor - $FeSO_4$
- Sodium Aluminate - $Na_2Al_2O_4$
- Lime, pH > 10

Chemicals used for Phosphorus Precipitation

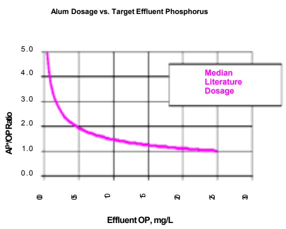
Chemical	*Formula*	*Removal mechanism*	*Effect on pH*
Ferric Chloride	$FeCl_3$ M.W. = 162.3	Metal hydroxides	Removes alkalinity
Aluminum Sulfate (Alum)	$Al_2(SO4)_3.14.3(H_2O)$ M.W. = 599.4	Metal hydroxides	Removes alkalinity
Ferrous sulfate (pickle liquor)	Fe_2SO_4	Metal hydroxides	Removes alkalinity
Poly Aluminum Chloride	$Al_nCl_{(3n-m)}(OH)_m$ $Al_{12}Cl_{12}(OH)_{24}$	Metal hydroxides	none
Lime	CaO, $Ca(OH)_2$	Insoluble precipitate	Raises pH above 10

Chemical Addition Rates

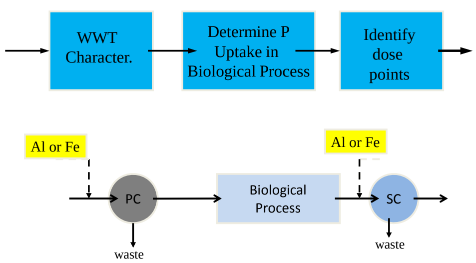
- Dependent on:
  - TP Discharge Limitations
  - Influx TP Loading
  - Biological P Removal Rates
  - Chemical to P Molar Ratios:
    - Al/Fe Salts, Range: 1.6- 2.1 to reach 0.5 mg/l P
      > 3.0 to reach < 0.25 mg/l P
      > 5.0 to reach < 0.2 mg/l P
      >10 to reach < 0.15 mg/l P
    - Dependent on Alkalinity

Phosphorus Removal w/Chemicals

- Add chemical to precipitate phosphorus
- Alum & ferric chloride
- Consumes alkalinity
- **Increases sludge production**



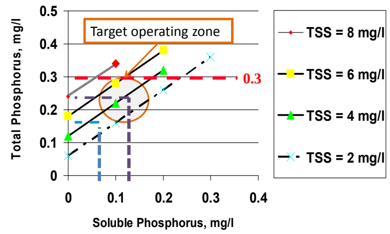
Chemical Addition Only Phosphorus Removal



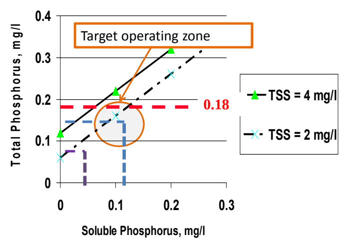
Gravity Filtration Application

- Removes Residual Bio-Floc
- Removes Residual Chemical/Bio Floc
- Removes Residual Coagulation Particles in Phys-Chem Treatment

Effluent TP versus Effluent TSS



Effluent TP versus Effluent TSS



Summary

Helpful Hints - Final Comments

Helpful Hints

- Consider multiple "barriers" for BOD, TN, and TP removal
- Nitrification is "Key" to successful nitrogen removal
- Nitrify completely – NH_3 < 0.1 mg/l; no NO_2^-
- Maintain < 0.1 mg/l D.O. in denitrification process to maximize denitrification rate

Final Comments

- Many possible causes for poor BOD and nutrient removal performance
- Important to determine cause and act quickly to maintain biological processes
- Basic troubleshooting approaches are universal
- Each plant should develop troubleshooting protocols that are specific to their specific processes, environmental conditions, and process control tools

Questions?

Thank You

"Anyone who can solve the problems of water will be worthy of two Nobel prizes – one for peace and one for science."

- John F. Kennedy

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