Optimization of Activated Sludge and Fixed Film ENR Processes through Automation

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Optimization of Activated Sludge and Fixed Film ENR Processes through Automation

WWW 6100

7 contact hours
9 CC10 hours

One of Maryland's top environmental priorities is upgrading wastewater treatment plants for nutrient removal. This class will discuss various automation options and operating practices currently used and available for removing nutrients from wastewater. The usage and cost of physical and biological technologies will be addressed. Dissolved oxygen and pH/ORP probes along with nitrate, ammonia, and phosphate analyzers will be discussed as to their role in automated process control. The accuracy and precision of today's analyzers now allows process control in addition to process monitoring. Other topics covered will include: the effluent concentration required as to the appropriateness of Enhanced Nutrient Removal (ENR) techniques; the importance of methanol dosing or another carbon source as a food source for denitrifying organisms; metal salt addition and effluent filtration for phosphorus removal; nutrient removal regulations pertinent to protecting the Chesapeake Bay; and operational issues related to TN and TP removal with recommended corrections.

1. Identify sources of nitrogen and phosphorus in wastewater.
2. Describe the chemical addition options for phosphorus and nitrogen removal.
3. Describe methanol dosing and other carbon sources.
4. Identify process control strategies for nitrification and denitrification.
5. Discuss loop control in automated processes.
6. Identify dissolved oxygen and pH/ORP probes and nutrient analyzers available for process control.

Agenda:

A. Overview (120 minutes)
    - Nutrients – Phosphorus and Nitrogen
    - Benefits of nutrient removal
    - Nutrient issues around the world
    - Chesapeake Bay Requirements
    - Limits of Technology (Depends on soluble organic concentrations)
    - Chesapeake Bay Discharge Permit levels
    - Why is nutrient removal process control optimization needed?
    - How does automation provide process control optimization?
    - Automated process control loops – Introduction
    - Meters, Probes, and analyzers
B. Nutrient removal – Basics (60 minutes)
    - Phosphorus
    - Nitrogen

C. Phosphorus Removal with Chemicals (30 minutes)
   - Fundamentals
   - Operational issues
D. Biological Nitrogen Removal – Overview (60 minutes)
   - Reference the Nitrogen Cycle
   - Show how nitrification and denitrification fit in the Nitrogen Cycle
   - Technologies
E. Nitrogen removal fundamentals (60 minutes)
   - Nitrification
   - Denitrification fundamentals
F. ENR - Nitrification and denitrification process units (60 minutes)
   - Common ENR processes:
   - With carbon addition
   - Operational issues
   - Process control optimization/automation
G. Post Test/Class evaluations (30 minutes)

Optimizing BNR/ENR Activated Sludge and Fixed Film Processes

with

Instrumentation, Controls, and Automation (ICA)

Process Training Sessions

Before class starts, please:

- **Sign in** on Attendance Sheet

During class, please:

- **Asks questions**
  - Feel free to get up and leave the classroom at any time (i.e., rest rooms, phone calls, etc.)

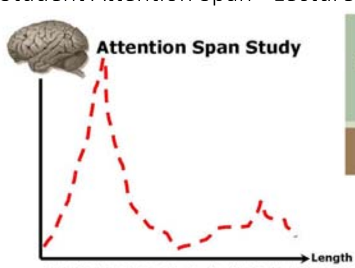
Housekeeping

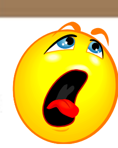
- 1–day class
- Start class – 8:00 am
- 10-minute Breaks – every hour
- Lunch ~ 11:30 am – 12:30 pm
- End class ~ 3:30 to 4:00 pm

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





Discussions

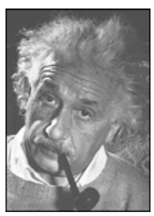
- Student involvement in class discussions is encouraged:
  - To keep students attentive
  - To help students retain information

The Guiding 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

Objectives of Class

1. Review BNR/ENR control strategies:
   - Nitrification:
     - DO control
     - MCRT/SRT (Activated sludge)
     - NH_3 mass loadings (Fixed film)
   - Denitrification
     - Internal recycle flow rates (Activated sludge)
     - Supplemental carbon (Methanol) feed
     - NO_3 mass loadings (Fixed film)
   - Phosphorus removal –
     - Enhanced biological uptake
     - Chemical feed rates (Clarifiers)

Objectives of Class

2. Review and discuss sensors used in BNR/ENR processes:
   - Accuracy and precision of sensors
   - DO probes
   - Ammonia probes/analyzers
   - Nitrate probes/analyzers
   - Phosphate probes/analyzers

Objectives of Class

3. Review and discuss instruments used in process control loops:
   - Process control loops: Feed back, feed forward, or combination
   - Transmitters and Cabling (Analog and digital)
   - Programmable Logic Controllers (PLC's)
   - Actuators (Motorized valves, VFD's (Pumps and blowers)

Expected Learning Outcomes

- Nutrient (TP & TN) removal processes:
  - Physical/Chemical
  - Activated Sludge
  - Fixed Film
- BNR & ENR process control strategies
- Instruments and automation controls used in BNR & ENR processes

Agenda

- ICA Drivers:
  - Advancing instrumentation, especially nutrient sensors
  - More stringent nutrient standards by regulatory agencies
  - Pressures for cost efficiency
- Evolution of wastewater treatment process strategies for nutrient removal
  - Activated sludge and fixed film processes
  - BNR to ENR
- Key process control parameters for optimizing BNR/ENR processes
  - Internal Recycle
  - Aeration
  - Carbon addition
- Phosphorus removal

PROCESS CONTROL LAWS

- **FIRST LAW**: The best control system is the simplest one that will do the job
- **SECOND LAW**: A process must be understood before it can be controlled
- **THIRD LAW**: Automated control is difficult if mathematical models and/or algorithms can not be developed

Instructor's Rules

- Rule # 1 – Automation is all around you
- Rule # 2 – Automation doesn't come to you …you go to it
- Rule # 3 – "There's no one trick pony"
- Rule # 4 – "There's no cure for the uninspired"

Automation Drivers

- Advancements in instrumentation
  - More accuracy and precision
- Increasingly more stringent water quality (Nutrients) standards:
  - Clean Water Act
  - Chesapeake Bay
- Improve process performance and cost efficiencies:
  - Internal Recycle
  - Aeration (Power)
  - Chemicals

Driver #1 for IC&A

Advanced Instrumentation:
Accuracy and Precision

IC&A

Overview

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 and cost efficiency
- BNR/ENR processes require effective DO control (enough but not too much)

Process Control

- Operators use a combination of probes and analyzers to monitor **and control** BNR/ENR processes:
  - DO
  - Nitrification (Ammonia profile)
  - Denitrification (Nitrate profile)
  - Phosphorus removal

Process Control Loops

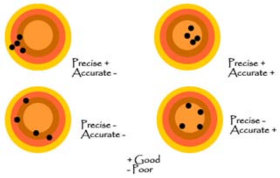
- Monitoring and control of a process
- WWTPs rely on four building blocks:
  - A process model concept
  - Monitoring and control strategies
  - **Sensors that provide accurate and precise on-line data to controllers**
  - Actuators or control elements that implement controller output

Process IC&A - What's Needed?

- Sensors – Probes and/or analyzers:
  - Accurate
  - Precise
- Communications network – Analog, digital, radio, and/or telemetric
- Controllers:
  - Modules or Remote Terminal Units (RTUs)
  - Programmable Logic Controllers (PLCs)
- Actuators, e.g., valves, pumps, blowers

Accuracy and Precision

- Accuracy: How close is it to the actual reading?
- Precision/Repeatability: Does it provide the same answer each time?



Why Automate?

- Monitor basic information about the processes
- **<u>Accurate and precise instrumentation</u>** is now available to automate system processes
- Eliminate manual measurements, e.g. dependency on delayed lab measurements
- Save time, save money, and increase efficiency
- Allow facilities to operate at limits of technology

Process Control

- WWTPs are never in a steady state; subject to “disturbances”
- A major incentive for automated process control is to minimize impacts of “disturbances” on plant processes:
  - Wastewater influent constituents, their concentrations, and flow rates
  - Discrete events such as rainstorms, peak loadings, and spills

Process Control

- Key factors in automated process control systems:
  - Responsiveness
  - Ability to deal with disturbances
- “A responsive control system” means the controlled variable responds quickly to adjustments in the manipulated variable
- Frequency and magnitude of disturbances should be minimum

Definitions

- **Input Variable** – This variable shows the effect of the surroundings on a process and normally refers to factors that influence the process:
  - *Manipulated inputs:* variables in the surroundings that can be controlled by an operator or the control system
  - *Disturbances:* inputs that can not be controlled by an operator or control system
- **Output variables**- Also known as *control variables;* these are variables that are outputs of the process.

Process Control

- Three physical properties are typically monitored in wastewater:
  1. Liquid flow: Influent/effluent, recirculation, return activated sludge (RAS), sludge wasting quantities, chemical addition
  2. Constituent Concentrations: DO, MLSS, BOD_5, TSS, nutrients, sludge solids
  3. Gas volumes: air, digester gas

Common Controlled Variables

- Aeration
- BOD_5 and TSS loadings
- Ammonia, Nitrate, and Phosphate loadings
- Chemical Addition
- Internal Recycles
- Sludge Wasting Rates

Common Controlled Variables

- Aeration
  - Set DO levels in different sections of process
  - Control aeration time (cyclic aeration)
- BOD_5 and TSS loadings
  - Maximize removal of BOD_5 and TSS before nitrification/denitrification
- Ammonia, Nitrate, and Phosphate mass loadings
  - Avoid overloading unit processes

Common Controlled Variables

- Chemical Addition
  - Methanol, Ferric/Alum, alkalinity feed rates
- Internal Recycles
  - Set recycle 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!

Nitrification-Related Process Instruments and Parameters

- Temperature
- Flow meters
- Flow rates:
  - Influent/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

Phosphorus-Related Process Instruments and Parameters

- Flow meters
- Flow rates:
  - Influent/Effluent
  - WAS
- pH/alkalinity
- Phosphate Analyzers
- Phosphate conc., mg/L

Before You Can Control a Process Variable, You Must be able to Monitor It with Reliable Sensors

What are sensors?

- Devices which measure a target variable
- Two components
  - Sensing Element
    - Tracks the variable being measured
    - Sends signal to transmitter
  - Transmitter
    - Converts signal for use on local display
    - Sends signal to controller/SCADA

Sensor image from:
http://www.capitolscientific.com/core/media/media.nl?id=51573&c=1250437&h=767af71ece59e1f9ec11

Sensors – Calibration and Validation

- Example: side-by-side grab sampling with immediate filtration/analysis and comparing grab value with instrument value
- Typically conducted three times per week dependent on plant and sensor

Three Main Sensor Types

- Ion Selective Electrode (ISE) probes
- Wet Chemistry (Colorimetric) analyzers
- Optical (UV) probes

Ion Selective Electrode (ISE)

- Probe-type sensors that use an ISE probe and reference electrode

Images Courtesy of S::CAN

Images Courtesy of WTW

Detection by ISE Probe

- Specific ions adhere to membrane on measurement electrode
- Those ions do not affect reference electrode
- Measure potential (voltage) difference
- Replace cartridge ~ 6-12 months

Nutrient ISE Probes

Brand	Model
YSI	VARiON (IQ SensorNet)
Hach	AN ISE sc
Endress & Hauser	ISEmax

Wet Chemistry (Colorimetric) Analyzers

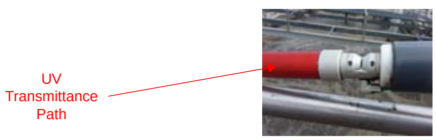
- Utilize a colorimetric method for measuring a constituent in a sample
- Withdraw a sample from the wastewater flow and pump it to a nearby analyzer

Images Courtesy of HACH®

http://www.capitalh2o.com/image/page_photos/chemscan_front.jpg

Optical (UV) Probes

- Utilize an ultraviolet (UV) light source to measure an absorbance and/or transmittance of UV light waves passing through a sample
- Similar to UV light absorbance spectrophotometers in a lab



Optical (UV) DO Probes

Brand	Model
YSI	FDO (IQ SensorNet)
Hach	LDO Model 2
Endress & Hauser	Oxymax
Insight IG	Model 1000
ATI	Q45D

Why are Sensors important?

- Automate data collection
- Monitor performance when no one is looking
- **Optimize process performance**
- **Minimize energy use and chemical consumption**
- Sensors can be paired with calibrated process models to enhance operations

IC&A Drivers

- Collect and record data for creating reports, profiling process performance, and storing data
- Reduce costs:
  - Operating costs, e.g. chemicals, energy (for aeration), labor
  - Capital costs, e.g., increase nutrient removal capacity by 10% to 30%; possibly reduce future system investments by another 20% to 50%

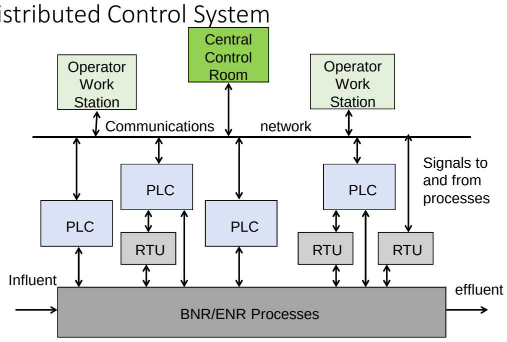
IC&A

Process Loop Control Concepts

Acronyms

- PSC – Process Control System
- DCS – Distributed Control System
- SCADA – Supervisory Control and Data Acquisition system
- PLC – Programmable Logic Controller
- RTU- Remote Terminal Units
- CMMS – Computerized Maintenance Management System
- LIMS – Laboratory Information Management System

Distributed Control System



Remote Terminal Unit (RTU)

- A direct interface between field sensors, actuators, and a central control unit
- A device to control multiple processes, without direct intervention from a controller or master

Programmable Logic Controller (PLC)

- Introduced around 1970 to replace electromechanical relay controllers
- Microprocessor-based
- Executes instructions/algorithms that implement logic, sequencing, counting, and arithmetic functions for controlling equipment and processes

PCs in Process Control

1. Operator interface – PC is interfaced to one or more PLCs or other devices that directly control the process
   - PC performs certain monitoring and supervisory functions, but does not directly control process
2. Direct control – PC is interfaced directly to the process and controls its operations in real time
   - Traditional thinking – risky!!

Loop Control Terminology

- **Open Loop control** – system where information about the controlled variable is not used (*no measurement*) to manipulate any of the process variables (e.g., based on observations)
- **Closed Loop control (feedback)** – system where the controlled variable (e.g., D.O.) is *measured,* compared to a setpoint, and action is taken to correct one of the process variables (e.g., Air flow)

Loop Control Terminology

- **Setpoint** is a "target" value for a process variable that is desired to be maintained
- **Error** is the difference between the measured variable and the setpoint
- **Algorithm** is a step-by-step (usually involving math) procedure used in automating process control, processing data, and reasoning; used in programmable logic controllers (PLCs)

Process Control Concepts

- Manual
- Feedback
- Feedforward
- Feedback/Feedforward
- Advanced Control

Manual Control

- Operator observes problems and takes corrective action
- Sometimes, nothing more than a guess
- "Open loop" control
  - No direct connection between desired output (setpoint) and process variable
  - Operator may have to constantly observe and change manipulated variable to ultimately correct problem

Automation Control Loops

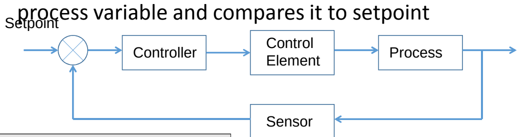
- **Feedback Control**: uses direct measurements of the controlled process variables (PV) to adjust the values of the manipulated variables
- **Feedforward Control**: uses direct measurement of the disturbances to adjust the values of the manipulated variables
- **Combined Control**: different combinations of the first two types
- Control objective - to keep control variables at desired levels, e.g., set points (SP)

Feedback Control Loop

- Feedback control is a common control strategy; its simplicity accounts for its popularity.
- The feedback controller works with minimum knowledge of the process; it needs only to know which direction to move
- How much to move is usually adjusted by trial and error

Feedback Control Loop

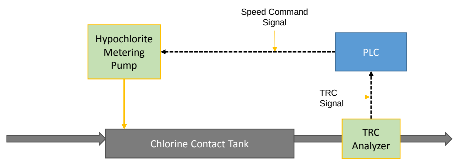
- Output information is used to adjust process controls
- Feedback controller receives sensor output on process variable and compares it to setpoint



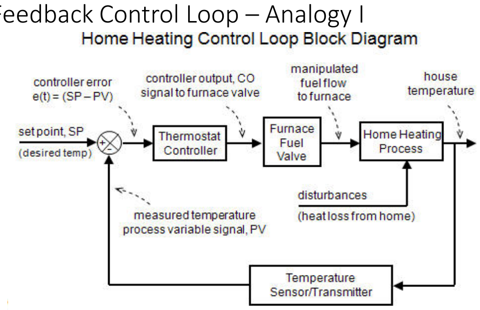
SISO – Single-input single-output

Feedback Control Loop

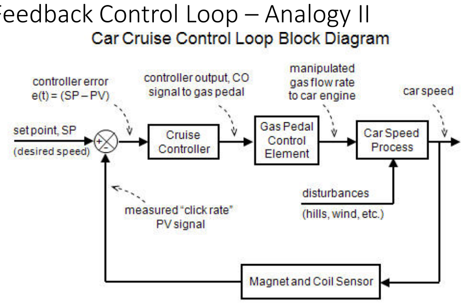
- Measurement is after the mechanical action (e.g., pump speed change)
- Example: Residual-based chemical feed



Feedback Control Loop – Analogy I



Feedback Control Loop – Analogy II



Feedback Control Loop

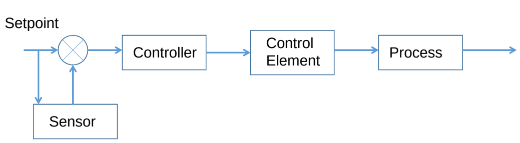
- Feedback control limitations:
  - Feedback control is after the fact, not predictive
  - Requires operators to change set points to optimize system
  - Changes can bring instability into system
  - Optimization of many input and output variables are difficult
  - Most processes are non-linear and change according to process environment

Feedback Control Loop

- Disadvantage of feedback control…it compensates for a disturbance only after the controlled variable has deviated from the set point
- Disturbance must propagate through the entire process before the feedback control scheme can initiate action to compensate

Feedforward Control Loop

- Input information is used to adjust process controls
- Controller receives sensor output on process variable and compares it to setpoint

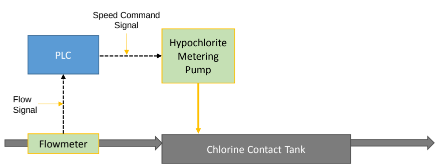


Feedforward Control Loop

- Objective - anticipate the effect of disturbances that will upset the process by sensing and compensating for them before they affect the process
- If applied correctly, the controlled variable deviation is minimum
- Mathematical model captures the effect of the disturbance on the process

Feedforward Control Loop

- Measurement comes before the mechanical action (e.g., pump speed change)
- Example: Flow-paced chemical feed



Feedforward Control Loop

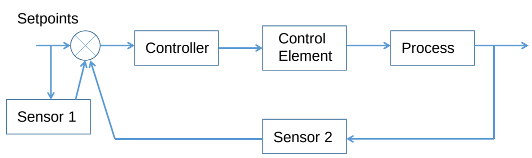
- Feedforward control avoids delays of feedback control
- Input disturbances are measured and accounted for before they have time to affect the system
- Difficulty with feedforward control:
  - Effects of disturbances on process must be anticipated
  - No surprises

Feedforward Control Loop

- Complete compensation for disturbances is difficult due to variations, imperfections in mathematical models, and imperfections in the control actions
  - Usually combined with feedback control
- **Feedback and feedforward controls are common in water and wastewater utility processes**

Feedback/Feedforward Control Loop

- Feedback and feedforward (e.g., compound) information is used to adjust process controls
- Controller receives sensor outputs on process input and output variables and compares it to setpoints



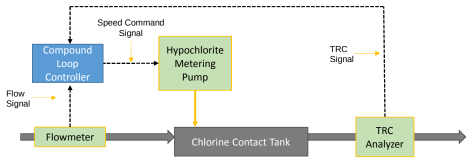
Feedback/Feedforward Control Loop

- Benefits of feedback control:
  - Controlling unknown disturbances
  - Not having to know exactly how a system will respond
- Benefits of feedforward control:
  - Responding to disturbances before they can affect process

Cascade control – Feedback as primary control loop with a feedforward secondary loop

Feedback/Feedforward Control Loop

- Measurement is made before mechanical action but adjusted based upon measurement downstream of the mechanical action
- Combination feed forward (FF) and feed back (FB) control



Advanced Control

- Use of computers and microprocessors
- Control logic (algorithms) includes feedforward and feedback control concepts
- Compare process conditions with pre-programmed conditions
- Best applied where multiple, parallel treatment units are used
- Monitors dozens of sensors
- Manipulates several pieces of equipment

Advanced Control

- Most complex processes have many control variables
- To control multiple variables, multiple control loops are used
  - Example: bioreactor with at least three control loops: Carbon feed, D.O., and flow splitting
  - Multiple control loops often interact causing process instability
- Multivariable controllers account for loop interaction
- Models can be developed to provide feedforward control strategies applied to all control loops simultaneously

Data Issues

- Inputs to advanced control systems require accurate, clean, and consistent process data
  - "Garbage in-garbage out"
- Many key process parameters cannot be measured on-line requiring laboratory or maintenance analyses
  - LIMS
  - CMMS
- Sensors may have to be filtered to attenuate noise
- With many variables to manipulate, control strategy is critical to limit control loop interaction

Driver #2 for IC&A

More Stringent Nutrient Removal Regulations

Regulatory Drivers

- 1972 Clean Water Act
  - EPA: Given authority to set nutrient water quality standards
- Chesapeake Bay Regulations
  - Biological Nutrient Removal Program (1980s – 1990s)
  - Enhanced Nutrient Removal Program (>2000)

Regulator Drivers

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 (Physical incorporation, 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 **water quality discharge standards** 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** (TSS, 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 issued discharge permit limitations

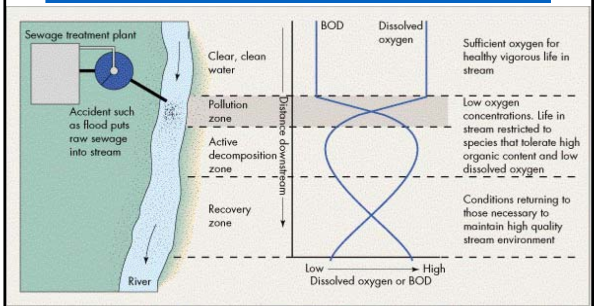
Wastewater Constituent Removal

- **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°C
    - DO uptake - 2.0 mg/l
    - DO remaining after five days -1.0 mg/l

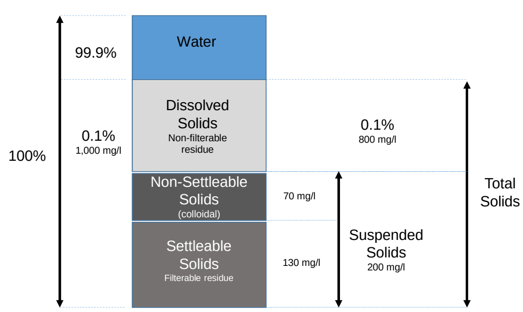
BOD Effects on Water Quality



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

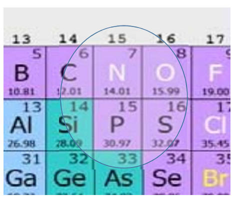


Key Wastewater Constituents

- 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

Nutrients

Part of the Periodic Table



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

Nutrients

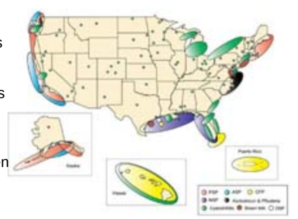
- TN – Total Nitrogen
  - Soluble and particulate
    - Organic nitrogen - N_{org}
    - NH_3 – Ammonia
    - NO_2 – Nitrite
    - NO_3 - Nitrate
- TP – Total Phosphorus
  - Soluble and particulate
    - PO_4 – Ortho-phosphorus
    - Organic
    - Polyphosphates

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.

Regulator 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

Nutrient Removal

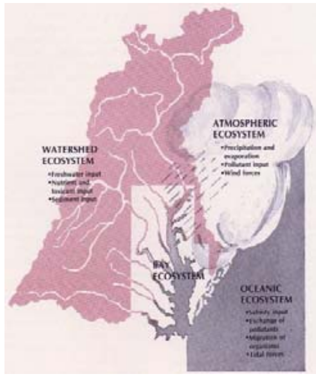
Nutrient | **Removal Process**

- 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

Ecosystems Affecting the Bay

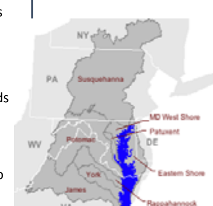


Chesapeake Bay Watershed

- 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**

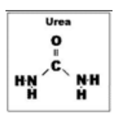


Nutrient Removal - Basics

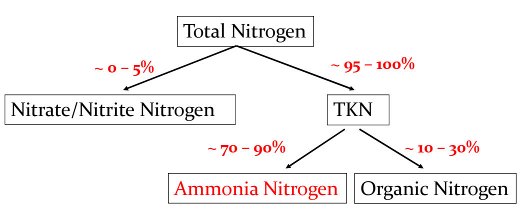
- In Bay watershed, **Nutrients (nitrogen and phosphorus)** contribute to algae growth
- Excess nutrients lead to excess algae growth
- Excess algae growth depletes oxygen and blocks sunlight penetration in water
- Submerged aquatic vegetation (SAV) dies off due to lack of sunlight (photosynthesis)
- Marine organisms die-off due to lack of DO

Sources of Nitrogen in Wastewater

- Human Wastes
  - Digested/wasted food (Proteins)
    - Vegetables
    - Meats
  - Urea (converted Ammonia)
- Cleaning products (Ammonia)



Forms of Nitrogen in Wastewater



Forms of Nitrogen

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

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)

NO_x (Oxidized)

Total Nitrogen (TN) = TKN + NO_x

TKN = Total Kjeldahl Nitrogen

Sources of Phosphorus in Wastewater

- Human Wastes
  - Digested/wasted food
  - Water softening products
- Organo-phosphorus flame retardants in children's clothing
- Corrosion and Scale Control
  - Sodium Hexametaphosphate

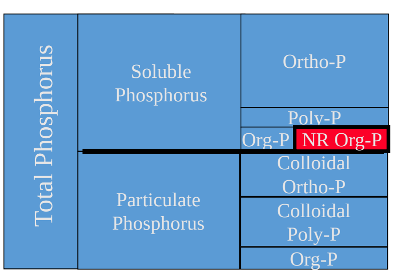
Phosphorus Compounds

- Commercial sources: Phosphate/Apatite rock
  - hydroxylapatite $Ca_5(PO_4)_3OH$
  - fluorapatite $Ca_5(PO_4)_3F$
  - chlorapatite $Ca_5(PO_4)_3Cl$
- Uses:
  - H_3PO_4 - Phosphoric Acid – soft drinks, fertilizers, and water conditioning (stabilization)
  - Sodium phosphates (ortho and poly) – water conditioning:
    - Na_3PO_4 – Trisodium phosphate
    - $Na_5P_3O_{10}$ - Sodium tripolyphosphate
  - Calcium phosphates:
    - $Ca(H_2PO_4)_2 \cdot H_2O$ - Additive in baking powder and fertilizers
    - $CaHPO_4 \cdot 2H_2O$ - Additive in animal food and toothpowder

Forms of Phosphorus

FORM	REMOVAL PROCESS
Organic-P	Converts to polyphosphate and orthophosphate forms; **a small soluble portion is non-reactive (0.05 mg/l)**
Orthophosphate	Most abundant form; chemically reactive and consumed by biological growth
Polyphosphates	Possibly reacts with metal salts; can be used for biological growth

Forms of Phosphorus



Wastewater Nutrients, mg/l

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

Raw Wastewater Concentrations, mg/l		
Nutrient	WWTPs, Average	Bay WWTPs Range
TN	35 – 40	30 - 45
TP	4.0 – 6.0	3.0 – 7.0

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/RBCs**
  - 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

Fixed Film Processes

- **Fixed-medium systems:**
  - **Trickling filters (TF)**
  - **Packed bed reactors (PBR)**
- **Moving-medium systems:**
  - **Rotating biological contactors (RBC)**
  - **Fluidized bed reactors (FBR)**

Uncovered Trickling Filter

Rotating Biological Contactor (RBC)

Fixed Film Processes

- cBOD Removal
  - TF – Trickling Filters
  - RBC – Rotating Biological Contactor
- Nitrification
  - BAF – Biological Aerated Filter
  - IFAS – Integrated Fixed-Film Activated Sludge
  - MBBR – Moving Bed Biofilm Reactor
- Denitrification
  - Denit Filter
    - Down flow
    - Up flow

Why use Fixed Film Processes?

- Considerably more biomass per unit volume than activated sludge
- Less land space is needed
- Relatively quick retrofits are possible
- Less expensive option to increase nutrient removal capacity

Nutrient Removal

BNR Program

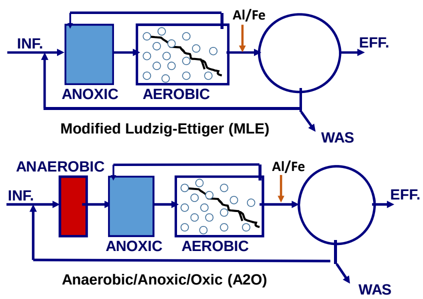
BNR Program

- 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

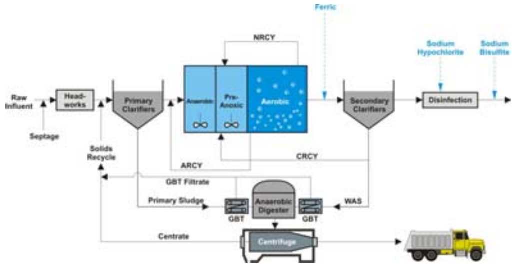
- To reduce total phosphorus concentrations, most WWTPs began adding chemicals like $FeCl_3$ or alum
- To reduce total nitrogen concentrations, most WWTPs initiated a capital improvement project to add "Pre" anoxic zones to already existing nitrification processes for partial denitrification

Biological Nutrient Removal



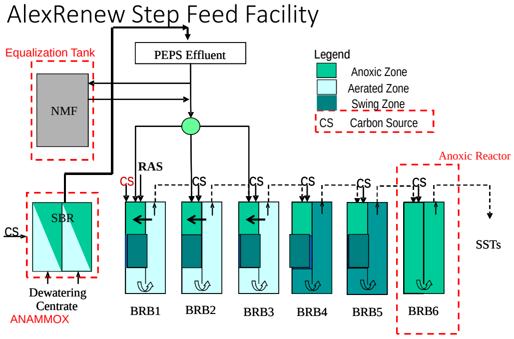
BNR

Typical BNR Activated Sludge System

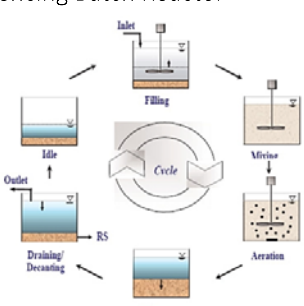


Modified Ludzack-Ettinger - MLE

AlexRenew Step Feed Facility



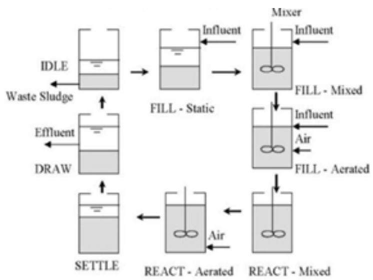
Sequencing Batch Reactor



Denitrification

Nitrification

Sequencing Batch Reactor



Oxidation Ditch

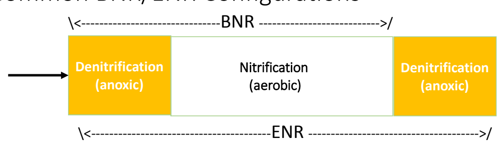
BNR Processes

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

Nutrient Removal

BNR to ENR

Common BNR/ENR Configurations

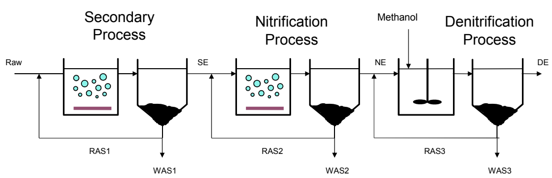


- BNR:
  - Modified Ludzack-Ettinger (MLE)
  - Anaerobic/Anoxic/Oxic (A2O)
  - University of Cape Town Process (UCT)
- ENR:
  - Enhanced MLE/4-stage Bardenpho
  - MLE with Denitrification Filter

Milestones

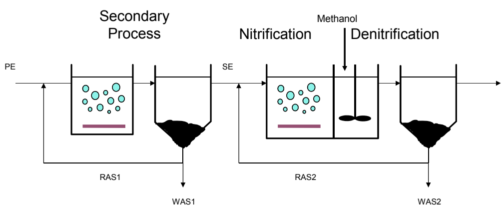
- 1968 Barth proposes 3-sludge, activated sludge process for nutrient removal
- 1970 Savage patents denitrification filter
- 1973 Barnard in South Africa develops the Modified Ludzack-Ettinger process, which becomes the standard for the wastewater industry

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

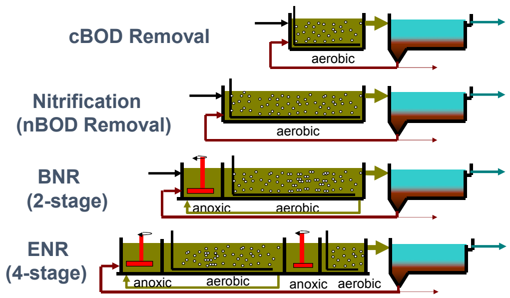


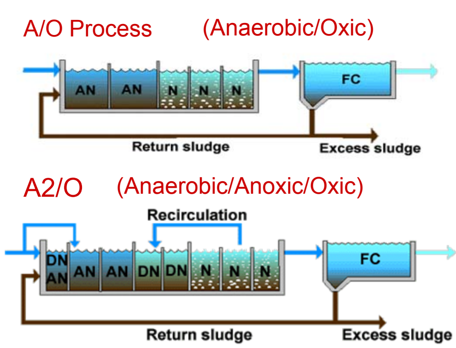
Blue Plains, DC Water 370 MGD (beginning early 1990s)

Milestones

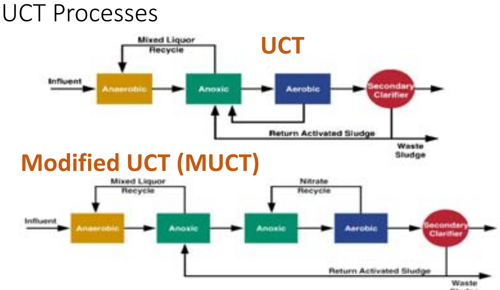
- 1975 Barnard patents Bardenpho® process
- 1976 Specter patents AO® and A2O® processes
- 1977 Jervis develops fluidized bed denitrification reactor
- 1980 University of Cape Town (UCT) process developed

Evolution of Activated Sludge



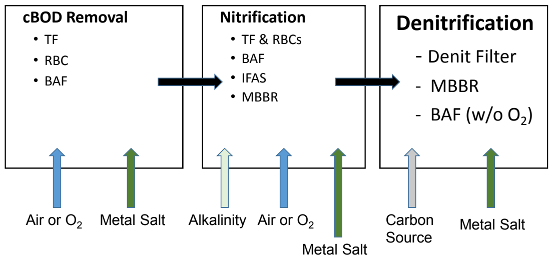


UCT Processes



For biological uptake of phosphorus and partial removal of nitrogen

ENR using Fixed Film Processes

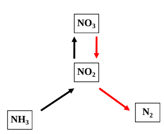


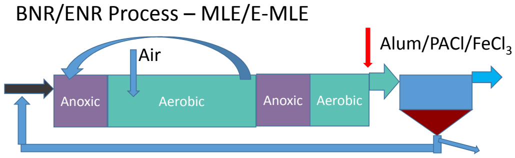
ENR Program

- 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

Nutrient Removal Strategies

- Nitrification (*Nitrosomonas, Nitrobacter, and Nitrospria*)
  $NH_3 + O_2 \rightarrow NO_2^- \rightarrow NO_3^-$
- Denitrification
  $NO_3^- + \text{organics} \rightarrow CO_2 + N_2$
- BNR/ENR Process – MLE/E-MLE





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

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

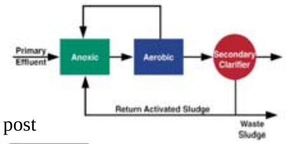
(a) Limit of Technology/State of the Art

Milestones

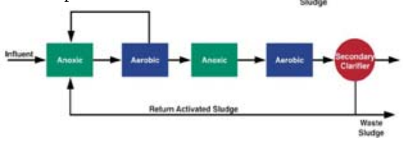
- 1975 Barnard patents Bardenpho® process
- 1976 Specter patents AO® and A2O® processes
- 1977 Jervis develops fluidized bed denitrification reactor
- 1980 University of Cape Town (UCT) process developed

Example of BNR to ENR

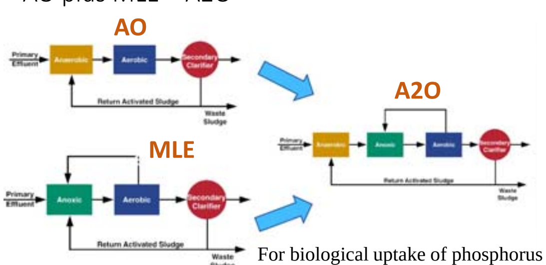
MLE



Enhanced MLE with post anoxic zone

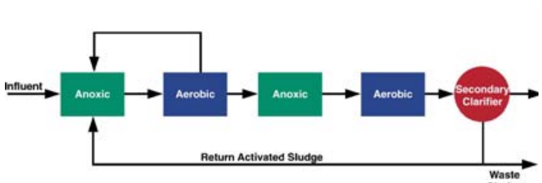


AO plus MLE = A2O

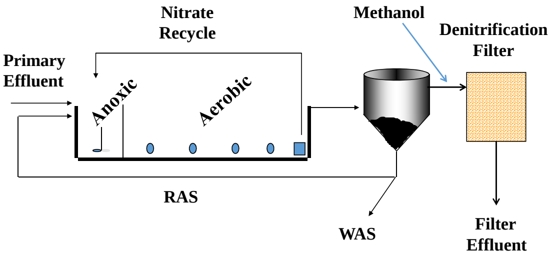


For biological uptake of phosphorus and partial removal of nitrogen

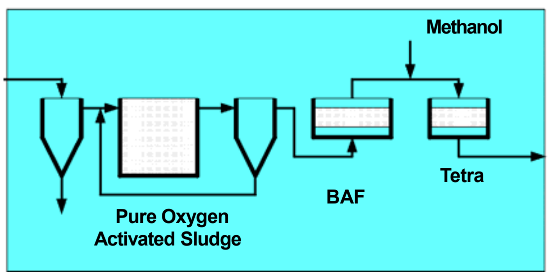
Bardenpho
(Enhanced Modified Ludzack Ettinger)



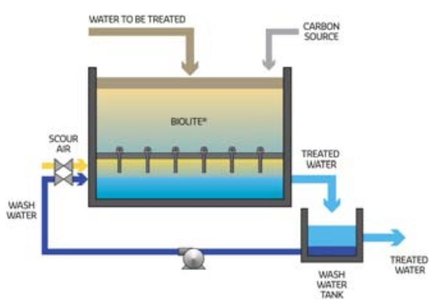
MLE With Denitrification Filter



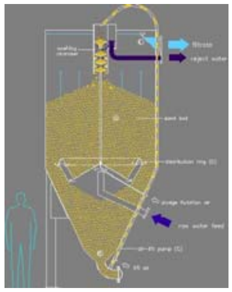
Patapsco WWTP
Baltimore, MD



Downflow Denitrification Filter



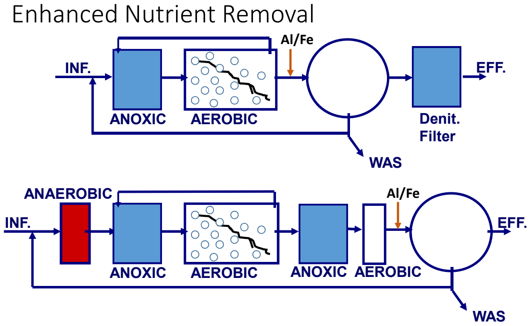
Upflow Denitrification Filter



ENR Program

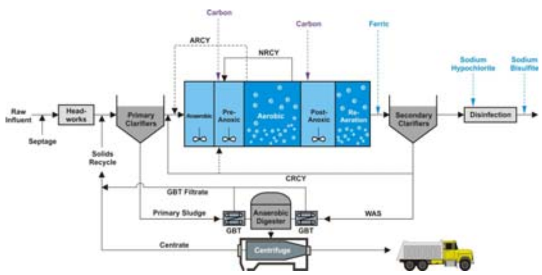
- To further reduce total phosphorus concentrations, most WWTPs began adding increased quantities of chemicals
- To further reduce total nitrogen concentrations, most WWTPs initiated a capital improvement project to add "Post" anoxic zones to already existing BNR facilities

Enhanced Nutrient Removal



ENR

Typical ENR Activated Sludge System



ENR Processes

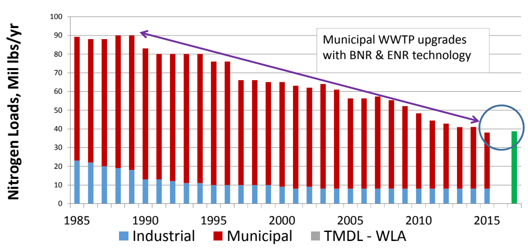
Process	Nitrogen	Phosphorus	Comments
Enhanced MLE (Bardenpho)	Excellent	None	- Large basin volume - Need for methanol
Modified UCT	Good	Excellent	-Separate anoxic zone for RAS - Several nitrate recycle streams - Increased complexity
5-stage Bardenpho	Excellent	Good	- Larger reactor volume - Need for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

Enhanced Nutrient Removal (ENR)

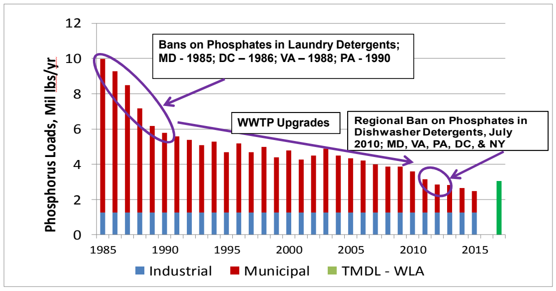
- Over the past two decades, BNR facilities have been upgraded with automation and new technologies to improve nitrogen removal efficiencies:
  - Integrated Fixed Film Activated Sludge (IFAS) to enhance nitrification
  - Mixed Bed Bio-reactors (MBBR)
  - Biological Aeration Filters (BAF) for nitrification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

TN Loadings to the Chesapeake Bay Wastewater

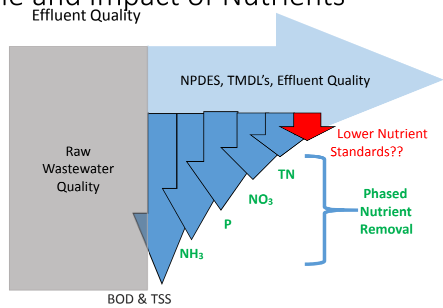
(Million pounds/year)



TP Loadings to the Chesapeake Bay Wastewater



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

BNR/ENR

Nitrogen Removal

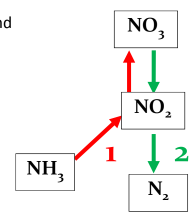
Keys to Successful Nitrogen Removal

- **Nitrification**
  - Adequate Aerobic SRT – **Keep Solids High!**
  - Adequate D.O./oxygen transfer
  - Adequate Alkalinity/pH
- **Denitrification**
  - **Successful nitrification**
  - Anoxic zones
  - No D.O
  - Carbon

Nitrogen Removal - Basics

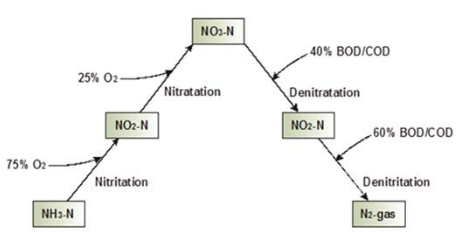
Nitrification + **Denitrification** = Nitrogen Removal

- 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)**



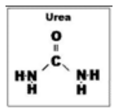
Simultaneous Nitrification and Denitrification (SNDN)

Traditional pathway of biological nitrogen removal

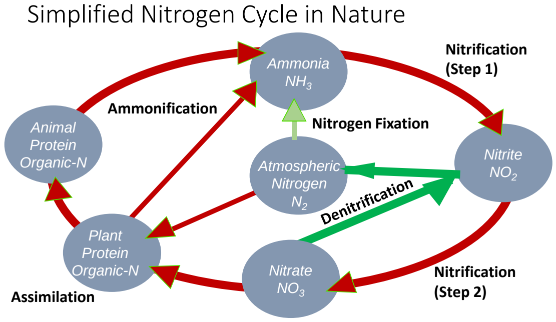


Sources of Nitrogen in Wastewater

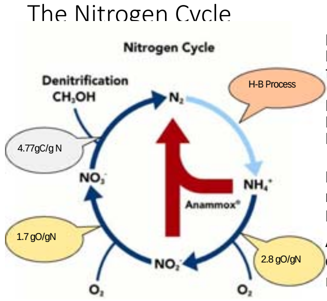
- Human Wastes
  - Digested/wasted food (Proteins)
    - Vegetables
    - Meats
  - Urea (converted Ammonia)
- Cleaning products (Ammonia)



Simplified Nitrogen Cycle in Nature



The Nitrogen Cycle



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

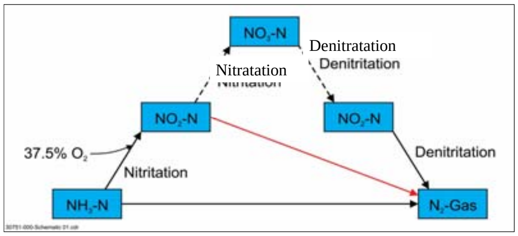
N/DN Uses O_2 for Nitrification, Carbon for Denitrification

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

Deammonification
“ANAMMOX”



Nitrogen removal

Nitrification

Nitrification Control Parameters

Temperature

- Nitrifiers lose about ½ their activity for each 10ºC temperature drop
- In winter, put additional aeration tanks on line, or increase MLSS
- Either action will increase MCRT

Nitrification Control Parameters

Dissolved Oxygen

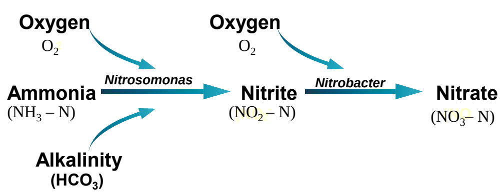
- Maintain MLDO at 2.0 – 4.0 mg/L

pH / Alkalinity

- Maintain MLpH > 6.8
- Maintain alkalinity residual of at least 70 mg/L

Two-step Nitrification

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

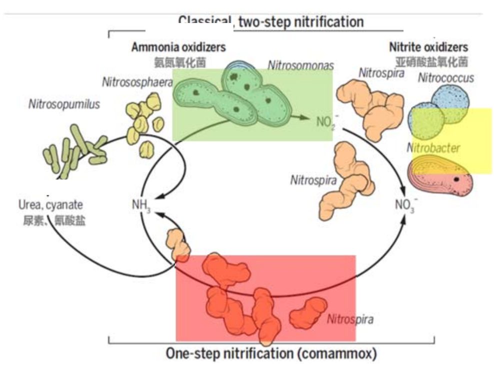


Two-step Nitrification

- Two-step nitrification depends on two organisms e.g., *Nitrosomonas* and *Nitrobacter*, which was the basis for hundreds of studies on wastewater nitrification
- A single microbe capable of catalyzing both nitrification steps may actually be a benefit by conserving more energy

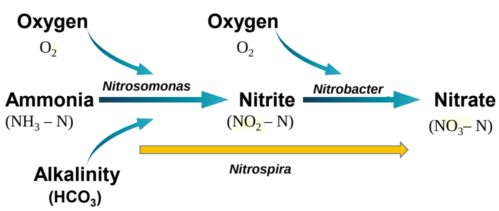
One-step Nitrification - Comammox

- **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 comammox organisms was confirmed within *Nitrospira*
- The Nitrogen cycle has since been updated

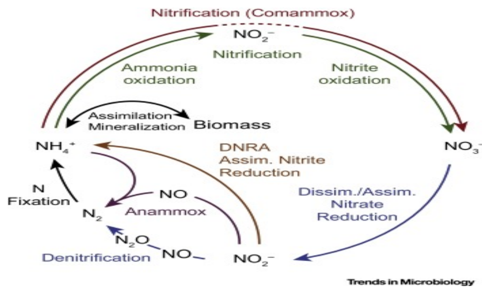


Nitrification

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



Environmental Conditions for Nitrification

- Nitrifying (Autotrophic) Bacteria
- CO_2 Carbon Source for Growth
- Sufficient SRT > 10 days
- Adequate Oxygen > 2.0 mg/l
- Adequate Alkalinity to prevent pH drop > 70 mg/l
- Process operating pH range – 6.5 to 8.0
- No Toxics or inhibitory compounds
- Temperature has a significant impact on process

Nitrification Process Controls

- Temperature
- Flow
- Wasting rate
- SRT
- DO in aeration zone
- pH/Alkalinity in aeration zone
- NH_3-N and NO_x-N probes:
  - End of aerobic zone
  - Plant effluent
  - At end of anoxic zones

Optimizing Nitrification

- Minimize influent BOD_5
- Optimize dissolved oxygen in aerobic zones
- Optimize internal recycle
- Last step: add alkalinity only if needed

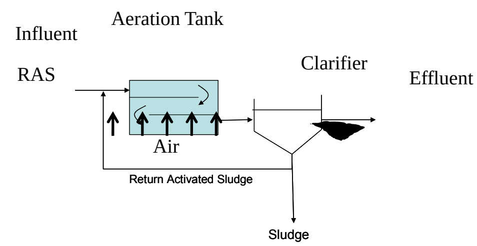
Obstacles to Achieving Nitrification

- Inadequate aeration capability
- Inadequate biomass quantity(MCRT)
- Poor clarifier hydraulics limiting MLSS in tanks
- Poor sludge settling/excessive filamentous bacteria
- Insufficient alkalinity
- Inhibitory chemicals

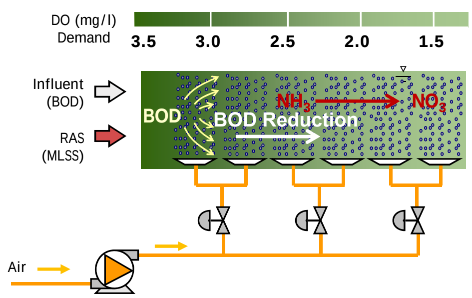
Nitrification Configurations

- Suspended Growth
  - Extended aeration AS
  - Oxidation ditch
  - Step feed AS
  - Sequencing Batch Reactor (SBR)
- Fixed Film
  - Up flow Biological Aerated Filters (BAF)
  - Moving Bed Biofilm Reactors (MBBR)
  - Integrated Fixed Film Activated Sludge (IFAS)

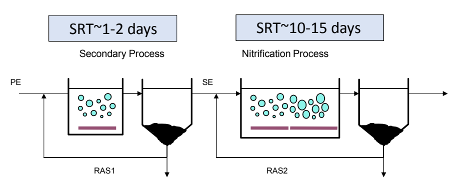
Typical Activated Sludge Process



BOD Removal and Nitrification



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



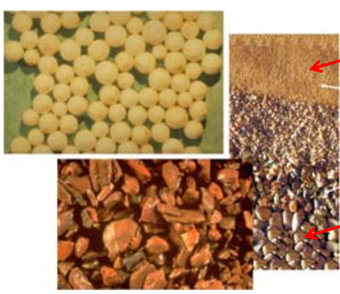
Blue Plains, DC Water 370 MGD

Western Branch, WSSC 30 MGD

BAF

- Biofor® - Up flow filter (Infilco Degremont)
- Biostyr® - Up flow filter (Veolia Water/Kruger)

BAF Media



Fine material
- Good filtration
- Large, specific surface area

Coarse material
- Less clogging

Submerged BAFs

BIOSTYR® Process

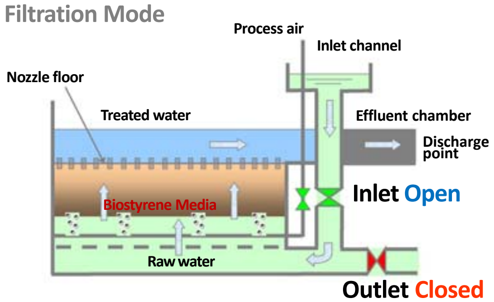
- Biological Aerated Filter (BAF)
- Fixed film process
- Removes biodegradable pollutants (carbon, ammonia and nitrogen compounds)
- Upflow filtration with floating media bed retained below nozzle floor

BIOSTYR® Process

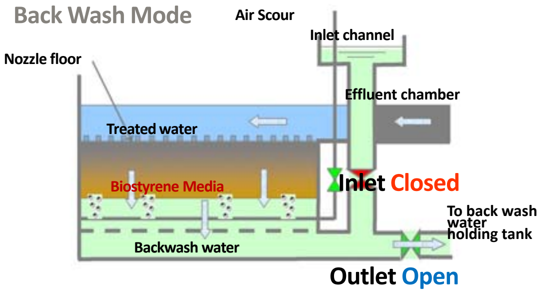
- Polystyrene beads (Biostyrene) provide surface area for biofilm growth and compact media bed for suspended solids removal
  - Typical media depth – 11.5 feet
- Backwashing utilizes treated water under gravity with air scour
  - Typical backwash interval – 48 hours
  - Typical backwash time – 30 minutes
  - Typical air scour – 4 minutes

BIOSTYR® Process

Filtration Mode

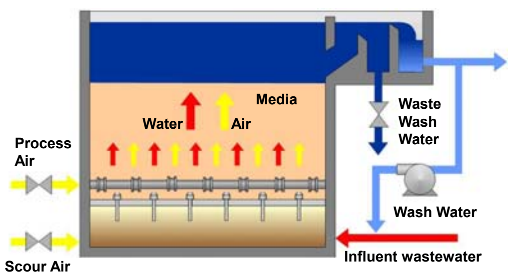


BIOSTYR® Process



Automation of BNR/ENR Processes 64

BIOFOR® Sequences



Automation of BNR/ENR Processes 65

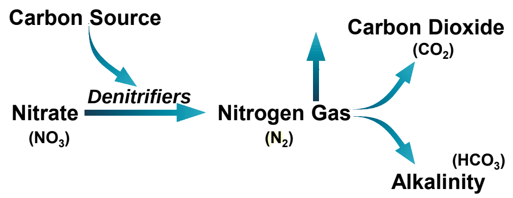
Nitrogen removal

Denitrification

Automation of BNR/ENR Processes 66

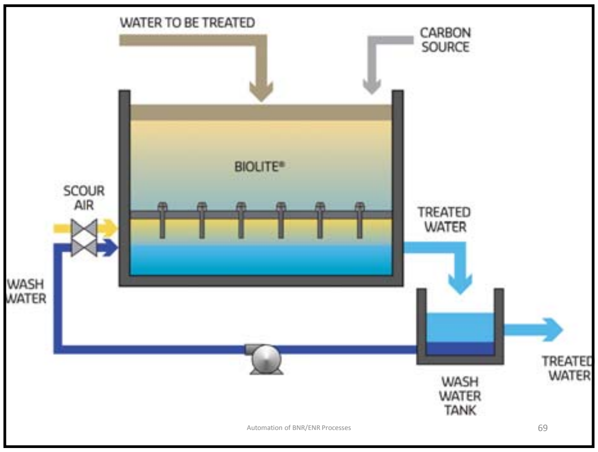
Denitrification

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



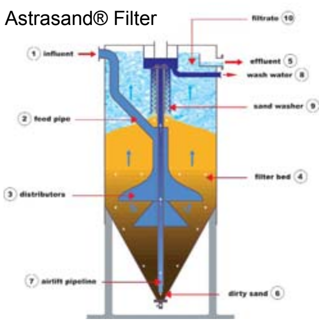
Denit Filters

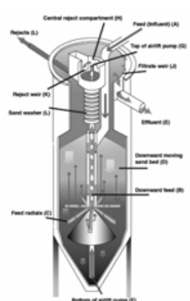
- Down Flow Denit Filters
  - Tetra Denite® System (Severn Trent)
  - Elimi-Nite® System (Leopold)
  - Davco Denitrification® System (Siemens)
- Up Flow Denit Filters
  - DynaSand® Filter (Parkson)
  - Astrasand® Filter (Paques/Siemens)
- Up Flow Fluidized Bed (Envirex)



The TETRA® Denite® system from Severn Trent Services removes nitrate-nitrogen and suspended solids in a single step. It is used as a tertiary process on effluents from wastewater treatment plants. TETRA was recently awarded a contract to supply their TETRA® Denite® system for use at the Baltimore City Patapsco WWTP.

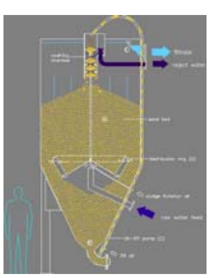
Up Flow Denit Filters





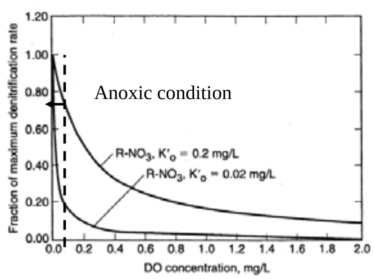
DynaSand® Filter

Up Flow Denit Filters



Up Flow Denit Filters

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



Comparison of Denitrification Filter Manufacturers and Equipment *

Manufacturer/ filter	Severn Trent Services/ TETRA® Denite®	F. B. Leopold/ elimi-NITE	USFilter/Davco	Parkson/ DynaSand	Paques and Siemens/ Astrasand
Flow regime	Downflow	Downflow	Downflow	Upflow	Upflow
Under drain	T-block; concrete-filled, HDPE jacket	Universal Type S HDPE block	Pipe lateral; or Multiblock HDPE block	None required	None required
Air header arrangement	SS box header; laterals beneath underdrain	SS header across filter; laterals	SS air header; 2-inch laterals	Vertical air lift	Vertical air lift
Media	18 inches graded gravel 6 ft of 6 × 9 mesh silica sand: uniformity coefficient - 1.35, 0.8 minimum Sphericity	15 inches graded gravel 6 ft of 6 × 12 mesh sand	2 layers support gravel, 6 ft of 6 × 9 mesh sand	1.35 to 1.45 mm subround media or 1.55 to 1.65 mm subangular media with uniformity coefficient of 1.3 to 1.6; 6.6-ft bed depth	1.2 to 1.4 mm sand, 6.6-ft bed depth
Nitrogen-release cycle	Initiated by headloss or time-controlled cycle; Speed Bump controls	Initiated by headloss or time-controlled cycle	Initiated by headloss or time-controlled cycle	None required	None required
Backwash water and air requirement	6 gal/min·ft^2); 5 scfm/ft^2	6 gal/min·ft^2 5 scfm/ft^2)	10 gal/min·ft^2); 5 scfm/ft^2)	Continuous through air lift and sand washer	Continuous through air lift and sand washer

Summary of Design Guidance for Denitrification Filters *		
Source	Hydraulic loading rate (gal/min·ft^2)	Mass loading rate (lb NO3-N per ft^3/d)
Manual: Nitrogen Control (U.S. Environmental Protection Agency, 1993)	1 to 2, 30 minutes empty bed contact time	0.018 to 0.1
Biological and Chemical Systems for Nutrient Removal, Special Publication (Water Environment Federation, 1998)		0.015 to 0.2 depending on temperature
Wastewater Engineering, Treatment and Reuse (Metcalf & Eddy, 2003)	1 to 2 at 20ºC	0.087 to 0.112 at 20ºC
	0.5 to 1.5 at 10ºC	0.05 to 0.075 at 10ºC
Severn Trent Services TETRA®Denite®	<3 at average flow; <7.5 peak hydraulic with one cell out of service	Determine using process model
F.B. Leopold	1 to 2	0.07
USFilter/Davco	2	NA
Parkson	4.5	0.015 to 0.12
Paques/Siemens	4.1	0.13

Denitrification Process Controls

- Temperature
- Flow
- Wasting rate
- SRT
- DO entering anoxic zone
- Carbon to nitrogen ratio
- NO_x-N probes:
  - End of aerobic zone
  - Secondary or plant effluent
  - At end of anoxic zones

Optimizing Denitrification

- Maximize the use of influent carbon
- Minimize dissolved oxygen to anoxic zones
- Optimization of internal recycle
- Maximize nitrification
- Last step: add supplemental carbon

Carbon for Denitrification

- Influent WW Carbon
  - Utilized in anoxic zones
  - Limited carbon available for secondary anoxic zones
- Supplemental Carbon
  - Methanol typically used
    - But requires methylotrophic population!
  - Alternatives to methanol – glycerin, sugars, and proprietary products

Carbon for Denitrification

- If using methanol – may not have adequate methylotrophic population
  - Need well controlled anoxic volume
  - Methylotrophs require acclimation time
- 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

Supplemental Carbon Sources

- Alcohols
  - Methanol
  - Ethanol
- Glycerol/glycerin – (Biodiesel by-products)
- Acetates - (Acetic acid, sodium acetate)
- Carbohydrates - (Sucrose, sugar water, corn syrup)
- MicroC™ – Carbohydrate (1000), glycerin (2000), alcohol (3000) based blends

Driver #3 for IC&A

Improved BNR/ENR Process Performances and Cost Efficiencies

Process Automation - What's Needed?

- Strategies:
  - Process control fundamental and/or "models" for TN and TP removal
  - Automation (loop) controls:
    - On-off
    - Proportional-Integral (PI) algorithms
    - Proportional-Integral-Derivative (PID) algorithms
    - With feed forward and/or feed back control loops

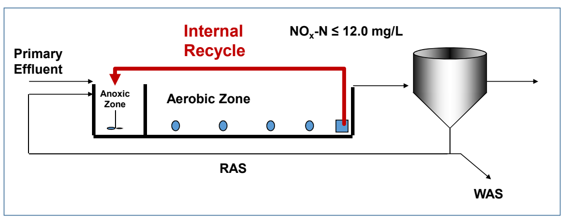
Process Automation - Strategies

- Optimize internal recycle
- Optimize aeration
- Optimize addition of supplemental carbon

BNR/ENR

Internal Recycle

Let's Focus on Internal Recycle



Internal Recycle

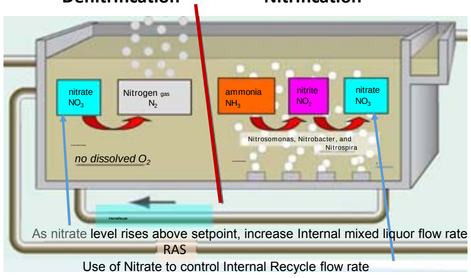
- Internal recycle flow rates determine nitrate concentrations in BNR process effluent
  - The higher the recycle flow rate, the lower the effluent nitrate concentrations
  - Process effluent nitrate concentration "set points" can be used to control internal recycle flow rates

Nitrate-Based Internal Recycle Control

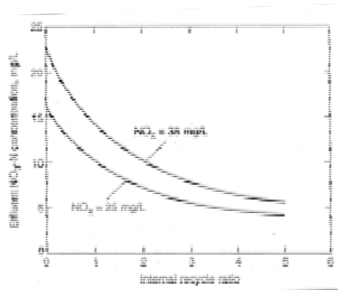
- As nitrate concentrations increase above set point in the nitrification zone (e.g., excess effluent nitrates)
  - Increase internal recycle from nitrification to denitrification
  - To decrease nitrates in nitrification effluent
  - To fully denitrify

Biological Nitrogen Removal

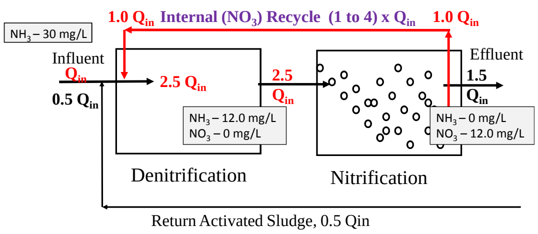
Denitrification **Nitrification**



Impact of Internal Recycle on BNR Effluent TN

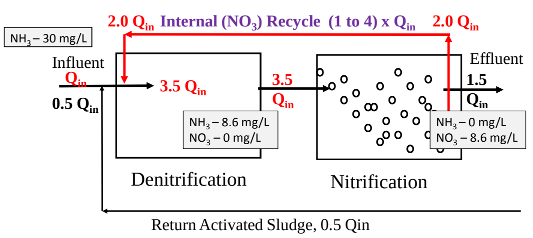


TN Removal – Example 1



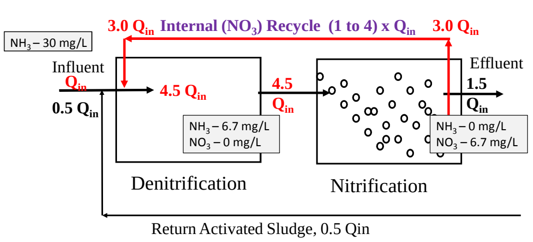
Assume all NO_3–N returned to Denitrification is converted to N_2
Assume all NH_3-N is converted to NO_3-N in Nitrification.
What is the NH_3-N concentration in Denitrification? $NH_3\text{-N} = \frac{30\ mg/L}{2.5/1} = 12.0\ mg/l$

TN Removal – Example 2



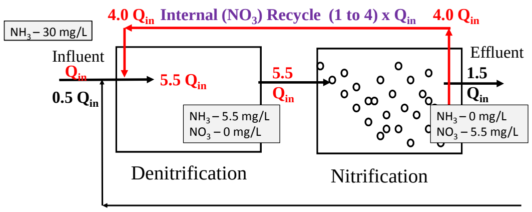
Assume all NO_3-N returned to Denitrification is converted to N_2
Assume all NH_3-N is converted to NO_3-N in Nitrification.
What is the NH_3-N concentration in Denitrification? $NH_3\text{-N} = \frac{30\ mg/L}{3.5/1} = 8.6\ mg/l$

TN Removal – Example 3



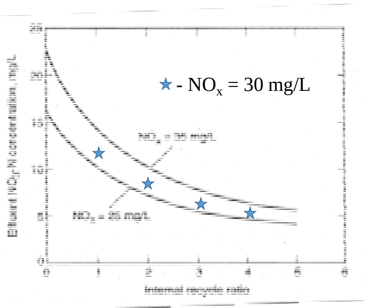
Assume all NO_3-N returned to Denitrification is converted to N_2
Assume all NH_3-N is converted to NO_3-N in Nitrification.
What is the NH_3-N concentration in Denitrification? $NH_3\text{-N} = \frac{30\ mg/L}{4.5/1} = 6.7\ mg/l$

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



Denitrification

Note: (Almost) all nitrates returned to the pre-anoxic zone are denitrified

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

BNR/ENR

Aeration

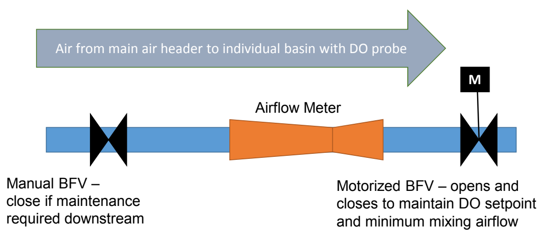
Let's Focus on Aeration

Aeration

DO-Related Process Controls

- Main header pressure
- Blower speed
- Number of blowers
- DO control valve positions
- DO probes
- Ammonia probe(s) (optional)

DO Control: Opening or Closing a MOV to Maintain a DO Setpoint

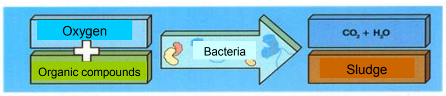


Aeration

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

Aeration

- Oxygen is used for growth of suspended and attached biomass to remove:
  - Soluble Organics (cBOD, COD)
  - Organic Solids (TSS, VSS)
  - Nutrients
    - Nitrogen
    - Phosphorus



Aeration

- Conventional biological processes are aerobic
- Many organisms in the activated sludge and fixed film processes need free oxygen (O_2) to convert food into energy for their growth
- Typical Dissolved Oxygen (DO) concentrations:
  - BOD removal - normal 1 to 2 mg/L
  - "Nitrification" - 2 to 4 mg/l

Aerobic Processes

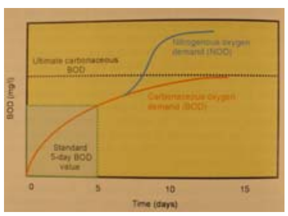
- Aerobic processes require O_2 for removal of organics (BOD) and conversion of ammonia-N to Nitrate-N (nitrification)
- Oxygen can be supplied by air or pure O_2
- Oxygen can be delivered through mechanical (surface) or diffused aerators

Aeration

- 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

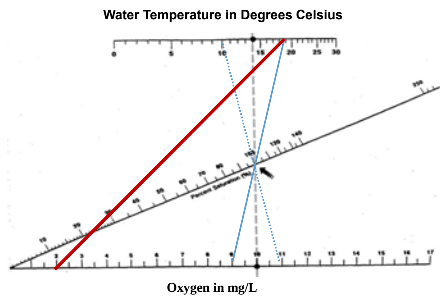
Treatment	Equation	lb O2/lb oxidized
Organic Removal	$BOD_{oxidized} = BOD_{inf} - BOD_{eff}$	1.0 – 1.2
Nitrification	$TKN_{oxidizable} = TKN_{inf} - TKN_{assimilated}$ $TKN_{oxidized} = TKN_{oxidizable} - TKN_{eff}$	4.6

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

Importance of Dissolved Oxygen

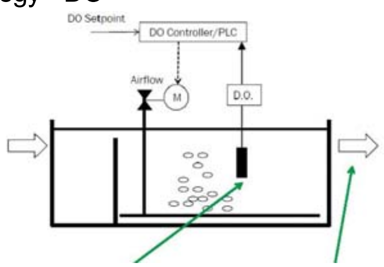
- Oxygen is sparingly soluble in water
- DO is a growth-limiting substrate
- *Critical oxygen concentration* is about 10% to 50% of DO saturation in water
  - 10% minimum saturation (~ 1.0 mg/l DO) for BOD removal to less than 15 mg/L
  - 20% minimum saturation (~ 2.0 mg/l DO) for complete nitrification

D.O. - Percent Saturation in Water



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

Typical MLE Aeration Basin Control Strategy - DO



New Aeration Basin Control Strategies

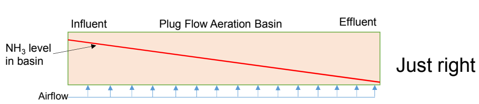
- Ammonia-based DO control
- Nitrate-based DO control

Objective of Ammonia-Based Aeration Control

- Aeration options:
  - Full nitrification
  - **<u>Incomplete nitrification</u>**
  - Reduce effluent ammonia peaks
- Potential benefits of incomplete nitrification include:
  - Decreased energy expenses (for aeration)
  - Possibly increased denitrification with less supplemental carbon addition
  - Possibly improved Bio-P removal

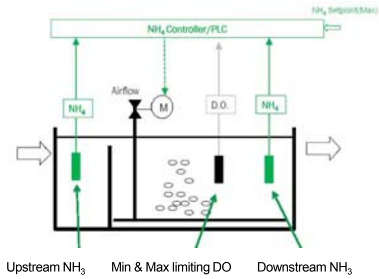
Ammonia-Based DO Control

- 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

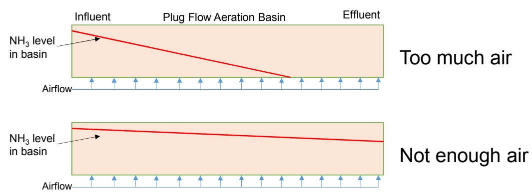


- When effluent ammonia is greater than setpoint, controller increases DO
- When effluent ammonia is below setpoint, controller decreases DO

Ammonia Feed Forward – Feedback Control



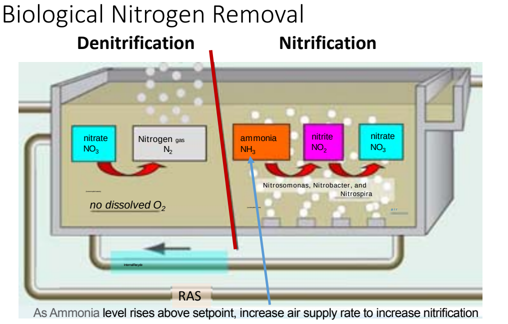
Ammonia-Based DO Control



Ammonia-Based DO Control

- As ammonia concentration increases above set point in the nitrification zone (e.g., ammonia breakthrough)
  - Increase aeration
  - To increase nitrification
  - To decrease ammonia concentration

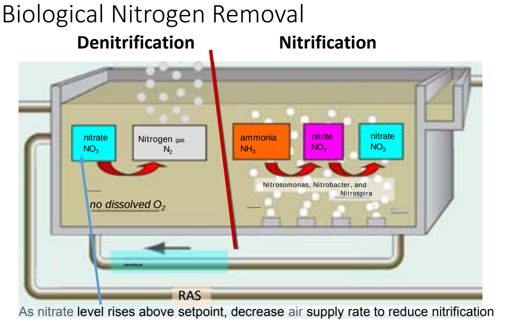
Biological Nitrogen Removal



Nitrate-Based DO Control

- As nitrate concentration increases above set point in the denitrification zone (e.g., incomplete denitrification)
  - Decrease aeration in nitrification
  - To decrease nitrification
  - To decrease nitrate concentration in recycle flow
  - To fully denitrification

Biological Nitrogen Removal

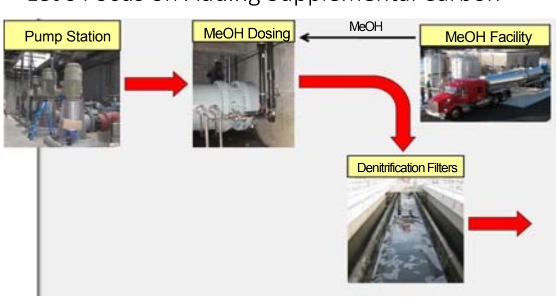


BNR/ENR

Adding Supplemental Carbon

Let's Focus on Carbon Addition

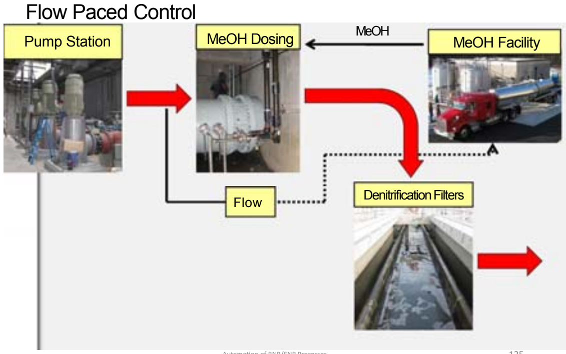
Let's Focus on Adding Supplemental Carbon



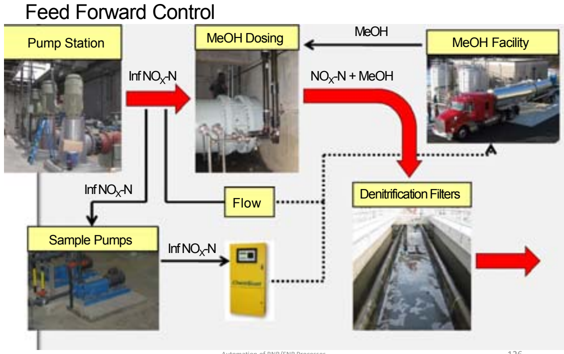
Adding Supplemental Carbon

- Typical control modes for supplemental carbon addition:
  - **Manual mode** – operator sets feed rate
  - **Flow-paced** – feed forward control: dose determined by desired nitrate removal – feed rate based on flow
  - **Nutrient-paced** – dual point control: paced based on nitrate load into anoxic zone; speed adjusted based on effluent nitrate concentration

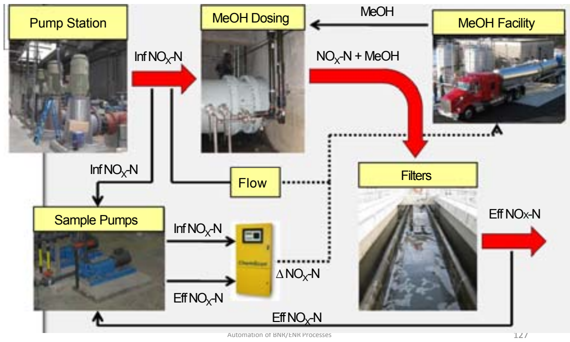
Methanol Dosing Strategy
Flow Paced Control



Methanol Dosing Strategy
Feed Forward Control

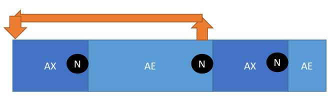


Methanol Dosing Strategy
Feed Forward/Feed Back Control



Adding Supplemental Carbon

- Nutrient-paced mode is the most accurate
  - Requires nitrate analyzers; locate in/out of anoxic zone and filters
  - With DO probe can account for DO entering the zone to improve results



Phosphorus Removal

Phosphorus Removal

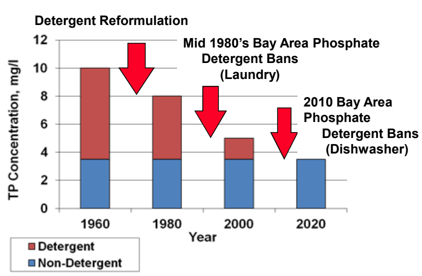
- Source control: Bans on phosphates in detergents (1980s and 2010)
- Background removal:
  - Physical incorporation (Clarifiers)
  - Biological uptake (Aeration)
- Chemical addition with metal salts (Clarifiers):
  - Al^{+++} (Alum, PACl) or Fe^{+++}($FeCl_3$)

Phosphate Bans in Detergents

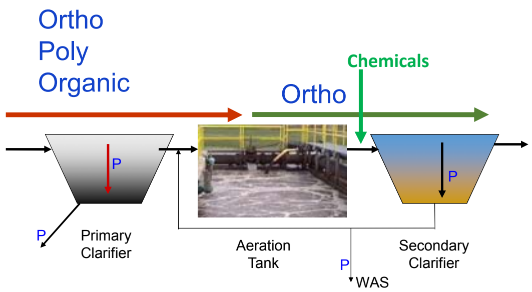
In the mid-1980's, Maryland, Pennsylvania, Virginia, and the District of Columbia instituted bans on phosphates in laundry detergents.

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

Typical Phosphorus Concentrations Raw Wastewater (@ 30% I/I)



Phosphorus Removal at WWTPs

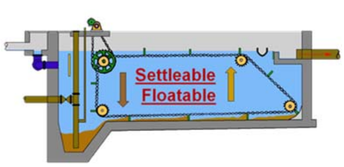


Background Removal

- Physical removal of particulate phosphorus
- Conventional Biological Uptake
  - To satisfy biological needs
- Enhanced Biological uptake
  - Stress induced
  - Release of phosphorus under anaerobic conditions
  - Uptake of phosphorus under aerobic conditions

Physical removal of Particulate Phosphorus

- Removal of settleable solids provides some phosphorus removal
- Primary sedimentation – 10 to 25%



Phosphorus Removal at WWTPs

- Removal of <u>Ortho-P</u>:
  - Biological uptake
  - <u>Enhanced</u> biological uptake
  - Chemical precipitation
  - Chemical adsorption

Biological Uptake

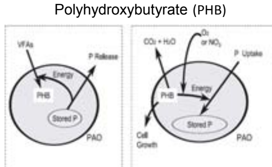
- Conventional Biological Uptake
  - To satisfy biological needs (1.5 to 2.0% by weight)
- Enhanced Biological uptake (5 to 7% by weight)
  - Stress induced
  - Release of phosphorus under anaerobic conditions
  - Uptake of phosphorus under aerobic conditions

Enhanced Biological P Removal

- Enhanced bio-P removal depends on:
  - Anaerobic conditions (zero dissolved oxygen and zero nitrate)
  - Volatile fatty acids (VFA, rbCOD)
  - Solids management (SRT, WAS, and side streams)

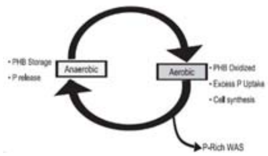
PAO - Phosphate Accumulating Organisms

PAO Able to <u>store soluble organics</u> as Polyhydroxybutyrate (PHB)

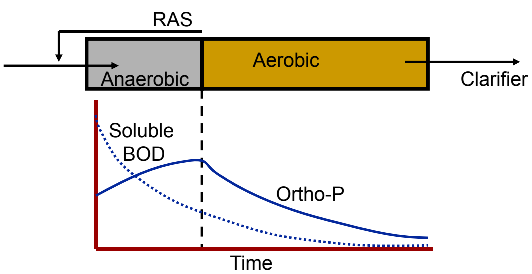


Enhanced Biological P Removal

- Step 1: Anaerobic Phase
  - BOD removal
  - Phosphorus release
- Step 2: Aerobic Phase
  - Phosphorus uptake and creation of new PAOs
  - Phosphorus removal by sludge wasting

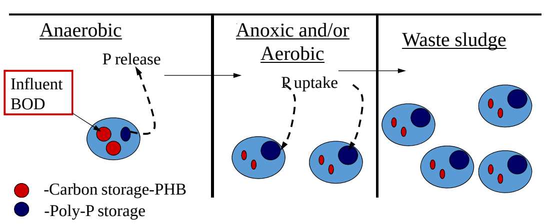


Enhanced Biological P Removal

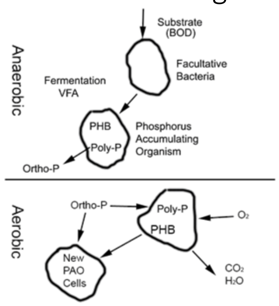


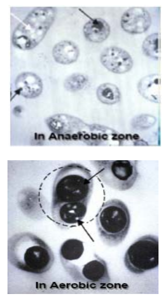
Enhanced Biological P Removal

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



Enhanced Biological P Removal

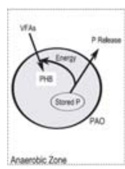




Enhanced Biological P Removal

Anaerobic Conditions

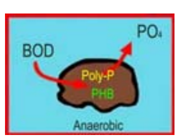
Heterotrophic Bacteria Break Down Organics
Fermentation
Volatile Fatty Acids (VFAs)
Acetate (Acetic Acid)



Also:
Selection of **PAO - Phosphate Accumulating Organisms**
(Able to Out-Compete Other Aerobic Heterotrophic Bacteria for Food When Anaerobic)

Enhanced Biological P Removal

Anaerobic Conditions



PAO Take Up VFAs and Covert them to Polyhydroxybutyrate (PHB)

PAO Able to store soluble organics as Polyhydroxybutyrate (PHB)

Ortho-P is Released Into Solution

Enhanced Biological P Removal

Aerobic Conditions

Rapid Aerobic Metabolism of Stored Food (PHB) Producing New Cells

PO_4 Used in Cell Production
Excess Stored as Polyphosphate
("Luxury Uptake")

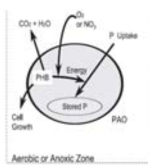
Enhanced Biological P Removal

Aerobic Conditions

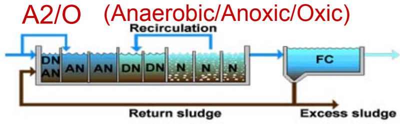
PO_4 Used in Cell Production
Excess Stored as Polyphosphate

Biomass 5 to 7% P by Weight

(Normal 1.5 to 2 %)

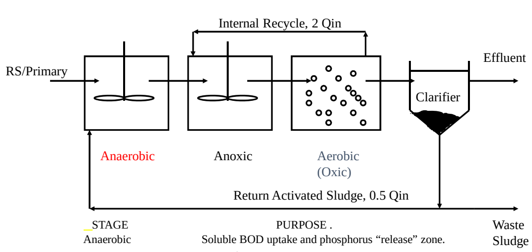


A2/O (Anaerobic/Anoxic/Oxic)



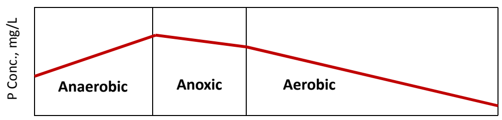
A20 Process

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

Phosphorus Profile – A2O



Anaerobic zone
P - Release

Anoxic and Aerobic zones
P - Uptake

Phosphorus Removal with Chemicals

Ortho Phosphates

React with

Metal Salts and Alkalinity

To form

Insoluble Phosphorus Compounds

Phosphorus Removal with Chemicals

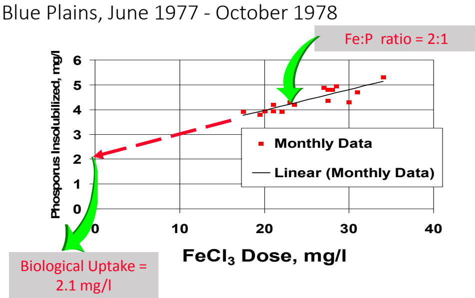
- Precipitation and adsorption with chemical addition:
  - Ferric chloride
  - Aluminum sulfate
  - Polyaluminum chlorides (PACl)
- With effluent filtration, TP concentrations can be reduced to ~ 0.05 mg/l

Phosphorus Removal with Chemicals

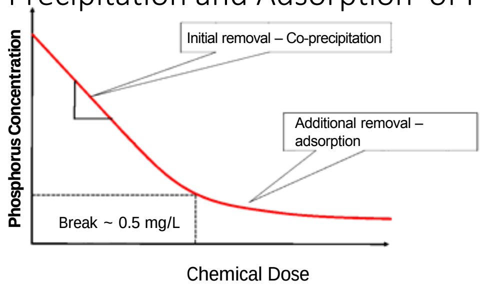
Chemical precipitation – two mechanisms:

- **Precipitation** (Remove TP to ~ 0.5 mg/l)
  - 2Al + 3OH + PO_4 ----> 2$Al(OH)_3PO_4$
- **Adsorption** (Remove TP < 0.5 mg/l to ~ 0.05)
  - *x* (Al + 3OH) ---> *x* ($AlOH_3$)
  - *x* ($AlOH_3$) + PO_4 ----> *x* ($Al(OH)_3$)·PO_4
  - *x* > 2; more chemical required as PO_4 levels drop
- Both reactions form Metal (Al or Fe)-Phosphate-Hydroxide sludge

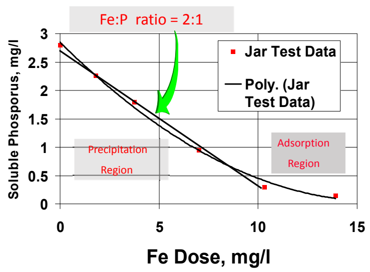
Precipitation of Phosphorus
Blue Plains, June 1977 - October 1978



Precipitation and Adsorption of P



Precipitation and Adsorption of P
Blue Plains - June 1977

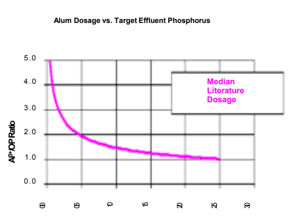


Chemicals used for Phosphorus Precipitation

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

Phosphorus Removal w/Chemicals

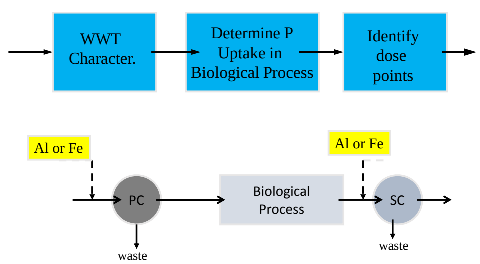
- Add chemical to precipitate phosphorus
- Alum & ferric chloride
- Consumes alkalinity
- **Increases sludge production**



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

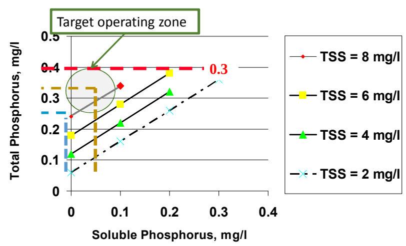
Chemical Addition Only Phosphorus Removal



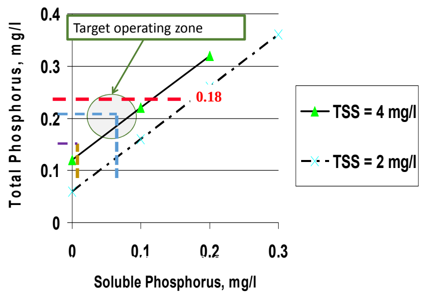
Gravity Filtration Application

- 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

Final Comments

- Today's DO, nitrate, ammonia, and phosphate probes and analyzers are extremely accurate and precise
- Probes and analyzers enable operators to make quicker decisions on any needed process control changes

Helpful Hints

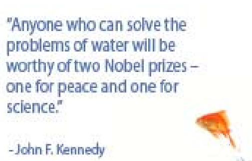
- Nitrification is "Key" to successful nitrogen removal
- Use a combination of DO and ammonia probes to optimize the nitrification process:
  - To conserve energy, aerate to ~ 1.0 to 1.5 mg/L DO to nitrify incompletely – NH_3 1 to 2 mg/L
  - To nitrify completely, aerate to ~2.0 mg/L – NH_3 < 0.1 mg/l; no NO_2^-
- Maintain < 0.1 mg/l D.O. in denitrification process to maximize denitrification rate

Helpful Hints

- Consider nitrate "set points" to control:
  - Internal recycle flow rates
  - Supplemental carbon feed rates

Questions?

Thank You



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