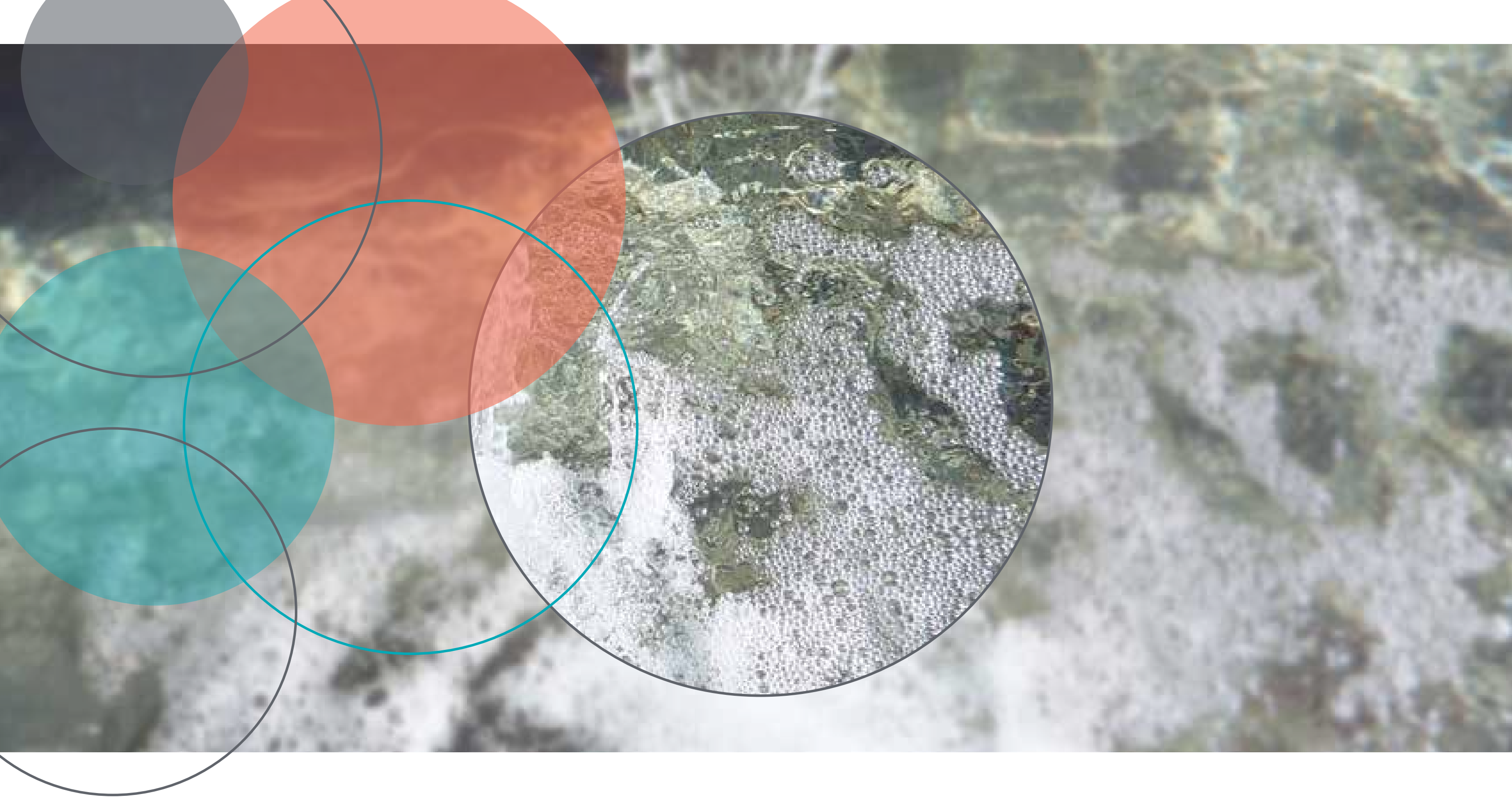

Operations and Control

MARCH 2019

The 2008 *Operations and Control Compendium* was prepared as part of the Nutrient Removal Challenge to provide guidance and address common questions related to nutrient removal water resource recovery facility operations. This 2019 compendium revision includes updates and references to reports and documents generated by researchers and contributors.

THE Water Research FOUNDATION

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The findings from the Nutrient Removal Challenge were incorporated into this 2019 edition by:

Bryce Figdore
HDR Inc.

JB Neethling
HDR Inc.

The following individuals contributed to earlier versions of this compendium:

Lead Editor:
Ryujiro Tsuchihashi
Metcalf & Eddy

Jeanette Brown
Stamford WPCA

Grant Davies
Metcalf & Eddy

Sam Jeyanayagam
Malcolm Pirnie

Salil Kharkar
District of Columbia Water and Sewer Authority

Mark Laquidara
Metcalf & Eddy

JB Neethling
HDR Inc.

Rob Smith
Malcolm Pirnie

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1199 North Fairfax Street, Suite 900
Alexandria, VA 22314-1445

6666 West Quincy Avenue
Denver, CO 80235-3098

info@waterrf.org
www.waterrf.org

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OVERVIEW

The purpose of this compendium is to summarize the current understanding, gaps of knowledge, and research needs in the operations and control of various nutrient removal processes. The types of nutrient removal considered include biological nitrogen removal, biological phosphorus removal, and physical/chemical phosphorus removal processes.

Topics are described in question and answer form. To help readers find specific topics, this compendium is divided into the following sections:

- Background and Definitions
- Design Considerations
- Process Fundamentals and Design Issues
- Operational Considerations
- Related Bibliography

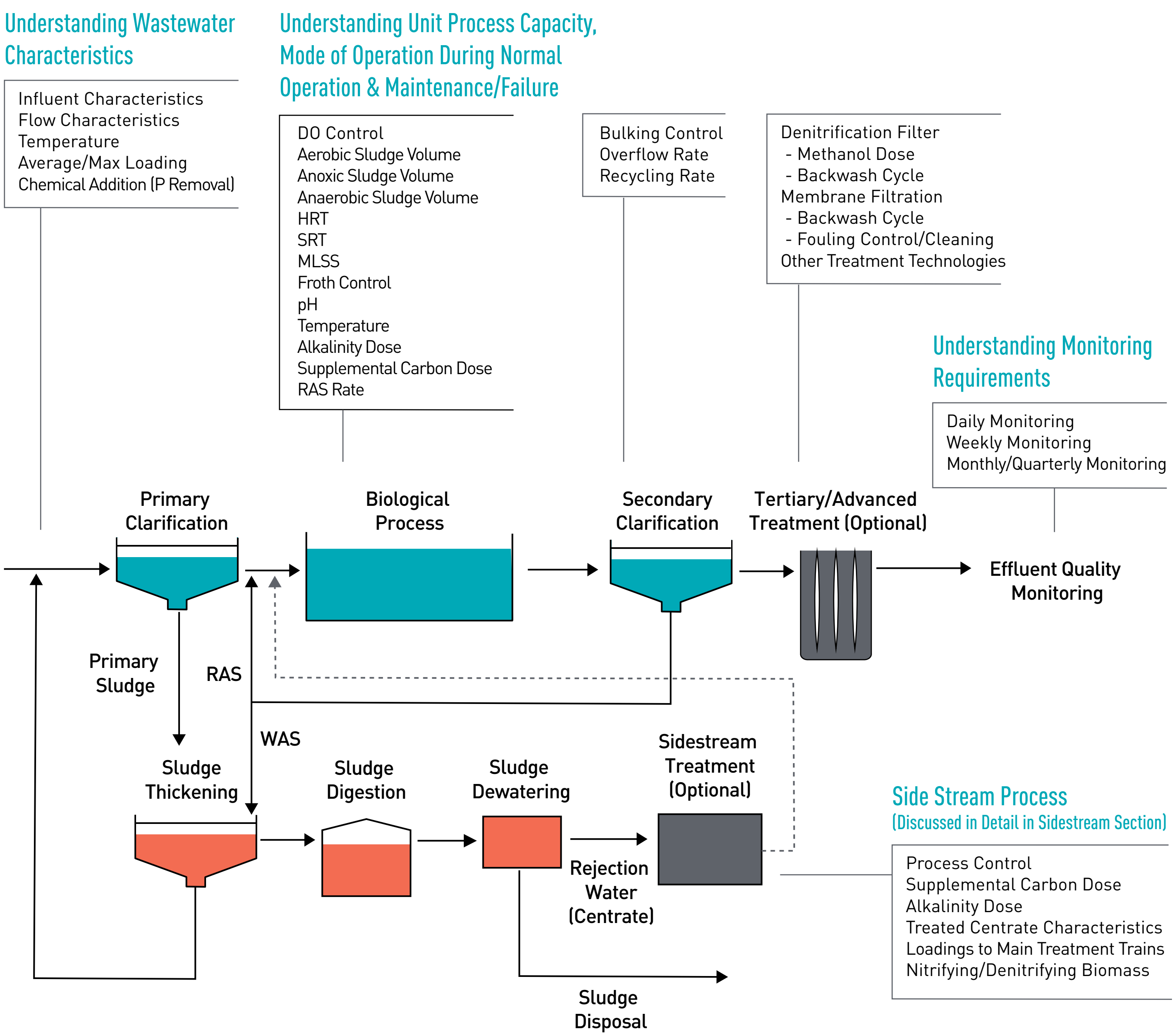
For topics requiring further study, research needs are included after related questions.

BACKGROUND AND DEFINITION

The diagram below illustrates a typical wastewater treatment system. The key operations and control issues relevant to nutrient removal are listed for each unit process. Each of the issues is further described in the following sections.

It should be noted that there are many different wastewater treatment configurations and some of them may not match the general configuration shown in the illustrated diagram.

Figure 1 - Key Operations and Control Issues in Nutrient Removal



What Are the Key Elements of Nutrient Removal Plant Operation?

A. Understanding Wastewater Characteristics

- Understanding wastewater characteristics, such as:
  - COD (and its bioavailability), BOD
  - TKN, Ammonium
  - Alkalinity
  - Solids (suspended, dissolved)
- Conditioning of, or adapting to, wastewater characteristics to come in line with critical ratios
- Understanding hydraulic and solids/nutrient loading factors on diurnal, 7-day, 15-day, 30-day rolling averages
- Understanding flow and loading balance, including:
  - Influent
  - Return Activated Sludge (RAS)
  - Waste Activated Sludge (WAS)
  - Gravity Thickener Overflow (GTO)
  - Stream from Sludge Thickening and Dewatering Process (centrate/reject water)
  - Digester Supernatant
  - Other Flows

B. Understanding Process Capacity/Reliability, Mode of Operation during Normal Operations, and Mode during Maintenance/Failure

- Capacity of existing facilities to meet permit compliance parameters
- Ability to maintain plant performance under the cold wastewater temperature and max month loading conditions
- Ability to maintain plant performance under wet weather conditions.
- Ability to alleviate and recover from plant upset by means of process redundancy and operating protocols
- Adequate screenings and grit removal to prevent this material from entering biological systems
- Multiple barrier approach to achieve limit of technology nutrient removal levels
- Adequate instrumentation and control of biological treatment systems—close monitoring of key parameters and making proper adjustments is key to success
- Adequate aerobic solids retention time (SRT) for nitrification
- Sizing and configuring systems to achieve realistic biological nutrient reduction—too small and too big are both problematic
- Adequate mixing and oxygen transfer systems in appropriate stages with no back-mixing that would compromise effect of the reactor compartmentalization

C. Understanding Biological Process Kinetics

- Minimum aerobic SRT to maintain nitrification
- Temperature effects
- Addressing inhibitory factors to reduced nitrification performance

D. Understanding Chemical/Physical Process Optimization

- Optimum chemical dosing for precipitation (P removal)
- Optimum loading rate for filtration processes (P, N)

E. Understanding Process Control (to be discussed further below)

- Hydraulic flow balancing to biological reactor and settling basins
- SRT control – Positive control of RAS and WAS rates to maintain MLSS target
- Optimize F/M gradient across biological reactors for bulking sludge control
- Configure inter-stage baffling to prevent or minimize back mixing
- Control of hydraulic currents within biological reactor and settling basins
- Managing plant recycle streams and associated impact to treatment performance

F. Understanding Monitoring Requirements

- Monitoring needs for process control versus permit requirements
- Analytical methods limitations and interferences

What Are the Key Elements of Nutrient Removal Process Control?

A. Control and Maintenance of Biomass

- SRT control—especially aerobic SRT—to maintain nitrification under maximum loading conditions and cold winter process temperatures
- RAS/WAS rate control – Must provide target F/M ratio and MLSS concentration that are consistent with the capacity of clarifiers

B. Control and Maintenance of the Operational Conditions to Maintain Biological Activity

- Adequate and effective oxygen transfer in oxic zones – DO matching demand across reactor basins – first oxic zone most critical to monitor and control where biological oxygen demand tends to be highest
- Monitoring of DO, nitrate (in and out of nitrification zones)
- Foster good floc-forming organisms and control sludge bulking
- Adequate and effective mixing in each zone – MLSS profiling through reactor basins to confirm adequate or expose problems – Portable MLSS probes are reliable – Need to calibrate permanent MLSS probes on a regular basis

C. Supplemental Chemical Addition as Needed

- pH/alkalinity control – An automated supplemental alkalinity (e.g. caustic) addition system with online pH probes is an effective control scheme, if required. Where online probes are not installed, pH may be monitored by portable probes but may not be effective in responding to diurnal variations.
- Supplemental carbon source dose control – Adequate monitoring of incoming nitrate/alkalinity/DO and outlet nitrate to optimize dose. Refer to a compendium on external carbon (WRF 2019a) for more detailed discussion.
- Coagulants (for physical/chemical phosphorus removal)

D. Control in Response to Variations in Operational Conditions

- Riding out the storm (literally and figuratively) – How to survive peak hydraulic conditions and reduce recovery period – Peak shave where possible or protect the biomass from washout
- Managing recycle streams to smooth out spike loading events
- Adjustments to process operation for diurnal loading variations
- Using online probes to set up a control algorithm

DESIGN CONSIDERATIONS

Many of the operations and control issues are dictated by the plant design. In this section, some of the design considerations that would affect the operations and control issues are briefly described.

What Instrumentation Should Be Used?

For a suspended growth nitrogen removal processes, the following instrumentation should be considered during the design phase.

Absolutely Necessary:

- **Influent and Effluent Flow Meters:** At a minimum, the plant must adjust to the diurnal variations in flow.

Highly Desirable:

- **Online DO Meter:** Control aerators based on the online DO monitoring; monitor DO intrusion in anoxic zones.
- **Online pH Meter:** Control alkalinity addition based on the online monitoring.

Desirable:

- **Online NH_3-N Meter:** Ammonia-based aeration control can be used to meet an ammonia concentration setpoint, obtain more stable nitrification throughout diurnal variations, and optimize aeration.
- **Online NOx Monitoring Sensors** (either as NOx or as nitrate and nitrite separately): Can be used in a feed-back control, or ammonium-N at the primary effluent; can be used in a feed-forward control for supplemental carbon addition.

Also see "What instruments should be considered for use in a nitrification/denitrification process?" on page 12.

What Design Considerations Would Make Operation and Control Easy and Reliable?

- Biological reactor configuration to promote efficient kinetic rates
- Effective oxygen transfer and mixing system
- RAS/WAS system to provide adequate SRT control
- Simple and reliable online control scheme

PROCESS FUNDAMENTALS AND DESIGN ISSUES

What Are the Most Important Process Elements for Nitrification?

- Adequate aerobic volume in biological reactor.
- Effective oxygen transfer and mixing system in biological reactor with sufficient blower capacity to maintain a DO of 2 mg/L. Lower DO concentrations may be possible, but increased reactor volume may be required to offset lower nitrification rates at lower DO concentrations. Recent research has indicated full nitrification at lower DO concentrations by growing a different nitrifier species.
- Adequate SRT control with a range of RAS/WAS rates to span start-up, design year, diurnal and seasonal operating conditions.
- Sufficient alkalinity to have at least 80 mg/L as $CaCO_3$ in the effluent and in bioreactors where nitrification occurs. If there is insufficient alkalinity in the influent, provisions must be made for adding it. It is critical to maintain a pH greater than 6.5.

Additional Considerations:

- Free Ammonia Inhibition: It is widely recognized that the presence of free ammonia can cause inhibition in the nitrification process with nitrite-oxidizing bacteria being more sensitive than ammonia-oxidizing bacteria, thus leading to nitrite accumulation. Free ammonia inhibition is particularly important for the side-stream treatment of high-strength ammonia-laden waste-waters such as centrate or filtrate. Free ammonia concentration is a function of total ammoniacal nitrogen concentration (NH_3 plus NH_4^+), temperature, and pH.
- Nitrous Acid Inhibition: It has been recognized that the presence of nitrous acid (un-ionized HNO_2) can cause inhibition in nitritation (ammonia oxidation to nitrite), especially in the side-stream treatment process. However, it is not recognized as an important issue in the mainstream process since the concentration in the main stream is not likely to be high enough to have any effect.

What Are the Most Important Process Elements for Denitrification?

The most important process elements for denitrification are reliable mixing, sufficient organic carbon, sufficient anoxic zone volume, and an environment with no or minimal DO. Deoxygenation zones are not necessary, but should be considered prior to anoxic zones to reduce or remove DO carryover from aerobic zones to anoxic zones. Residual DO carryover to anoxic zones decreases denitrification efficiency and increases supplemental carbon demand.

External Carbon Sources

- Available Carbon (electron donor)
- Volume
- Nitrate Recycle
- DO (or lack thereof)
- Endogenous versus Substrate Level Denitrification

Refer to WRF 2019a for more detailed discussion of the use of external carbon for biological nitrogen removal.

Additional considerations:

- Nitrous Oxide Generation: It has been reported that the denitritation process (reduction of nitrite) may generate nitrous oxide (N_2O), a potent greenhouse gas, at a much higher rate than denitrification from nitrate.
- Two-step Denitrification Process: It has been recognized that reduction of nitrate and nitrite appears to occur at a slightly different rate, sometimes resulting in accumulation of nitrite.

What Process Elements Are Important for Enhanced Biological Phosphorus Removal?

- Anaerobic zone design
- Configuration of recycle streams to anaerobic zone and associated oxygen and nitrate recycle loads
- Influent volatile fatty acids concentration and fermenter design, where necessary. Refer to WRF 2019b for more detailed discussion of the use of fermenters for enhanced biological phosphorus removal.

What Process Elements Are Important for Chemical Phosphorus Removal?

- Multipoint chemical injection (metal salts including ferric chloride, alum, etc.)
- Low effluent total phosphorus (TP) limits may require tertiary chemical addition and filtration.

Refer to WRF 2019c for additional details covering chemical phosphorus removal with a focus on tertiary phosphorus removal to meet low effluent phosphorus concentrations.

OPERATIONAL CONSIDERATIONS

What Are the Primary Operational and Control Considerations?

Nitrogen

Nitrification

Primary operational and control considerations include maintaining DO at or above 2 mg/L. Aerobic SRT is in the range of 6 to 8 days and possibly higher. Other considerations include maintaining a pH greater than 6.5 by adding alkalinity, if necessary; understanding the metabolic needs of the autotrophic organisms; understanding the in-line instruments to monitor ammonia and nitrate concentration, as well as DO; and being able to taper the air at the discharge end of the aerobic zone if the plant is also doing denitrification with mixed liquor recycle.

DO Control: If an online DO control system is not available, the operator needs to keep eyes on the DO level. Sometimes the operator may adjust the air flow on the safer side, resulting in a much higher than 2 mg/L DO. While this may be more than adequate for nitrification, setting the aeration to a higher than necessary DO level can be a waste of energy and also potentially result in DO intrusion in the subsequent anoxic zone to prevent effective denitrification.

SRT Control: Control of aerobic SRT is based on the inventory in the aerated biomass in terms of MLVSS versus VSS leaving the system. Minimum SRT requirements depend on the temperature; aerobic SRT must be longer under the cold weather conditions. Depending on the temperature, the minimum aerobic SRT is typically in the range between two and six days (WEF and ASCE/EWRI 2005). Appropriate safety factors should be considered in order to operate the process not too close to the minimum SRT.

pH Control: If the current system does not have an automated alkalinity addition, it is relatively easy to set up an online pH meter integrated with the alkalinity addition system to automatically adjust the alkalinity addition. Otherwise, alkalinity addition must be adjusted according to the daily pH monitoring data.

Denitrification

General Approach: The anoxic zone must be maintained with low to no DO and uniform mixing throughout. DO monitoring in the anoxic zone is recommended. To achieve low to no DO in the anoxic zone, a deoxygenation zone prior to the anoxic zone is often included to minimize the introduction of DO from the mixed liquor recycle. It is recommended to maintain an SRT greater than 12 days. It is important to understand the metabolism of heterotrophic organisms.

DO Control: As mentioned above, high DO levels in the aerated zones may result in DO intrusion in the anoxic zone. DO levels should be maintained at less than 2 mg/L in the zone immediately before the anoxic zone. A deoxygenation zone can help reduce the chance of DO intrusion in the anoxic zones.

Mixed Liquor Recycling: The purpose of the mixed liquor recycle is to supply nitrate for denitrification in the anoxic zone. The recycle flow rate should be controlled so that DO introduced to the anoxic zone will not adversely affect denitrification. A deoxygenation zone may be needed to minimize the DO intrusion into the anoxic zone and maximize use of influent carbon for denitrification.

Tertiary denitrification processes are addressed separately in another compendium (WRF 2019d). In instances where low nitrogen and phosphorus concentrations must be met, process staging should aim to have denitrification upstream of phosphorus removal to ensure the biological denitrification step is not phosphorus-limited and avoid the potential need for supplemental phosphorus addition.

Phosphorus

Enhanced Biological Phosphorus Removal

SRT Control: Phosphorus-accumulating organisms (PAOs) mediate enhanced biological phosphorus removal (EBPR) and grow slightly slower than ordinary heterotrophic organisms. A minimum aerobic SRT of approximately 2 days is needed for EBPR over a broad range of temperatures (Grady et al. 2011). EBPR is achieved by incorporating phosphorus into the biomass and wasting biomass from the system. Therefore, EBPR may be adversely impacted by excessively long SRTs with minimal wasting; such operations should be avoided. Practical maximum SRTs are near 30 days, however, phosphorus removal performance not be as efficient as at lower SRTs.

Anaerobic Conditions: Anaerobic zones select for the growth of PAOs, which can take up substrates under anaerobic conditions unlike ordinary heterotrophic organisms. Volatile fatty acids (VFAs) are a key substrate, although recent studies on RAS fermentation indicate that some PAOs may be more metabolically diverse and capable of using different substrates. Excessive mixing should be avoided to minimize surface oxygen transfer and disturbance of anaerobic conditions. Mixing energy near 2 W/m3 using slow-speed top entry mixers has been used with good results (Barnard et al. 2017).

Recycle Loads: Dissolved oxygen and/or NOx-N in return streams directed to the anaerobic zone can disturb anaerobic conditions as well as consume VFAs or other substrates which PAOs could otherwise utilize for growth and phosphorus removal. Such DO and/or NOx-N return loads are not fatal flaws, per se, but may adversely impact EBPR performance or stability, particularly for wastewaters with low VFA concentrations. Process operation and/or configuration should seek to avoid or reduce such return loads where possible. Refer to WEF MOP 29 (WEF and ASCE/EWRI 2005) for examples and discussion of EBPR configurations.

Competition with GAOs: Glycogen-accumulating organisms (GAOs) have a similar metabolism as PAOs but do not store polyphosphates and thus do not provide EPBR; thus, they can be thought of as competitors to PAOs. GAOs growth is favored over PAO growth as pH decreases below 7 and temperature increases to near 30°C. Typically, such operating conditions are beyond the control of operations staff. New technologies such as WAS hydrocyclones or granular sludge SBRs tend to selectively waste GAO biomass, which has lower density and slower settling rates than PAO biomass. Consequently these selective wasting approaches favor PAO growth and stabilize EBPR performance.

Chemical Phosphorus Removal

Removal Mechanism: Metal salt addition produces metal hydroxides. Phosphorus is removed by surface complexation on the metal hydroxide particles. Most phosphorus is removed rapidly during initial metal hydroxide formation. After initial formation, the phospo-metal hydroxides have additional phosphorus sorption capacity, although this sorption occurs at much slower rates. Mixing increases the amount of phosphorus removed per metal salt added and thus chemical phosphorus removal efficiency for a given chemical dose. These considerations are most relevant where tertiary chemical phosphorus removal is need to meet low P concentrations. Refer to the "Tertiary Phosphorus Removal" compendium for additional details and discussion (WRF 2019c).

Mixing: Chemical should be added to well-mixed location. For tertiary phosphorus removal to low concentrations, flash mixing zones should be considered to optimize chemical dose.

Chemical Dosing: Multipoint chemical addition is recommended for flexibility and reliability.

Supplemental Alkalinity: Metal salt addition consumes alkalinity. Supplemental alkalinity may be required if resulting alkalinity is too low to sustain efficient nitrification or effluent alkalinity and/or pH limits are not met.

Chemical Sludge Management: Facilities with tertiary chemical phosphorus removal can leverage the phosphorus sorption capacity of the chemical sludge by sending tertiary chemical sludge to the secondary process, where the chemical solids provide additional phosphorus removal. The secondary process SRT and amount of chemical sludge returned affect the extent of this "bonus" phosphorus removal in the secondary process. The overall plant chemical dose can be lowered by such a strategy. In a different scenario, facilities with efficient EBPR in secondary treatment and chemical phosphorus removal in tertiary treatment may seek to recovery phosphorus as struvite. Strategies to segregate chemical sludge from the EBPR solids stream going to phosphorus recovery are recommended to maximize P recovery. One such strategy is to recover phosphorus from a WASSTRP™ process and introduce tertiary chemical solids downstream in the combined solids to anaerobic digestion.

What Kind of Parameters Must Be Monitored and How Frequently?

Daily: pH, MLSS, MLVSS, TKN, SKN, COD, and SCOD. If in-line instruments are not available, then NO_3, NO_2, NH_3-N, and DO should be added to the daily list (daily means five days per week).

Three Times per Week: BOD_5

Once per Week: $sBOD_5$, TP, and orthoP

What Instruments Should Be Considered for Use in a Nitrification/Denitrification Process?

Plant personnel and designers should consider the installation of dissolved oxygen, nitrate, ammonia, MLSS, and pH sensors. ORP may also be considered depending on the owner's preference. These instruments will allow data to be collected through SCADA and operators to better monitor, control, and optimize the process.

Where Should These Instruments Be Located?

The following table shows the potential locations for instruments in a nitrification/denitrification process. Not all locations may be applicable to the particular process. Additionally, it may not be necessary or recommended to install instruments in all locations depending on plant and staff size and discharge limits. The table is intended to provide a summary of options that should be considered.

Table 1 - Potential Instrument Location in Nitrification/Denitrification Process

Instrument Parameter	Location(s)	Purpose	Comment
Ammonia	• Secondary Influent • Aerobic Zones • Secondary Effluent	Monitor loading, reactor ammonia profiles, aeration control	Process monitoring and optimization; evaluate diurnal loads; stabilize nitrification performance
NOx-N NO_3-N NO_2-N	• Anoxic Zones (including pre-anoxic and/or post-anoxic) • Aerobic Zones Prior to Nitrate Recycle or Post-anoxic Zone • Zones Immediately Preceding Post-anoxic Zones (such as aerobic or deoxygenation zones) • Secondary Effluent	Monitor performance, determine nitrate load on anoxic zone, control external carbon dose	Process monitoring and optimization; evaluate diurnal loads; stabilize denitrification performance
DO	• Aerobic Zones	Aeration control, ensure proper nitrification environment	May be used together with ammonia-based aeration control; Process monitoring and optimization. Reduce blower energy demand. Anoxic or deoxygenation zones may be checked for residual DO in troubleshooting, but typically do not have online DO probes installed.
pH	• Aerobic Zones • Effluent	Process monitoring, supplemental alkalinity control, ensure proper nitrification environment	Process monitoring and optimization; stabilize nitrification performance
ORP	• Anoxic or Anaerobic Zones • Aerobic Zones	Monitor redox conditions, aeration control	Useful to tell if zones are truly anoxic or anaerobic. Some processes use ORP-based aeration control.

How Will Aerobic SRT Affect the Nitrification Process? What Should Be Considered for Process Optimization?

Generally, an aerobic SRT of four days or more is desirable under moderate to warm weather conditions when maintaining nitrifying biomass. A longer aerobic SRT will be required during the cold weather season, when the wastewater temperature falls below 15°C. Refer to WEF MOP 29 "Biological Nutrient Removal Operation in Wastewater Treatment Plants" (WEF and ASCE/EWRI 2005) for additional information.

What Kind of Process Control Schemes Can Be Used for External Carbon Feed?

Carbon augmentation feed control strategies include the following: (1) manual control; (2) automatic flow-paced control; (3) automatic feed-forward control using flow and influent nitrate concentration; and (4) automatic feed-forward and feedback control using flow, influent and effluent nitrate concentrations. The last two modes, although increasingly complex, are considered essential when low TN levels are required. They rely heavily on online monitoring systems. Newer instruments are more durable and maintain their calibration for longer periods, thus allowing such control approaches to be applied successfully and reliably. Patented instrumentation packages aimed at providing very low effluent nitrate levels while maintaining low BOD and TOC concentrations are also available.

What Kind of Permitting May Be Required?

When external carbon is used to enhance denitrification, specific permits may be required to handle and store the external carbon source. For example, the use of 100 percent methanol is subject to a permit by the fire department for the handling and storage of flammables (Class 1B). Depending on the characteristics of the external carbon, other types of permits may be required.

What Safety Issues Are Associated with Methanol as a Carbon Augmentation Source?

Methanol is a colorless, volatile liquid with a faintly sweet pungent odor similar to ethyl alcohol. The substance is fully soluble in water. Vapors of methanol are slightly heavier than air and may travel some distance to a source of ignition and flash back. Accumulations of vapors in confined spaces, such as buildings or sewers, may explode if ignited. Methanol is highly flammable, with a flash point of 12°C (54°F). There is the potential for containers of the liquid to rupture violently if exposed to fire or excessive heat for a sufficient duration of time. Methanol is listed as a "Poison-Class B." It is harmful if swallowed or absorbed through the skin. Ingestion of as little as one ounce can cause irreversible injury to the nervous system, blindness, or death. It cannot be made nonpoisonous. Methanol also causes eye and respiratory system irritation and may cause skin irritation. Liquid, mist, or vapor contact should be avoided. Vapor inhalation or liquid penetration of the skin can also cause central nervous system depression.

What Are the Challenges in Process Control?

- Wet weather, cold weather conditions. The prevention of washout of the mixed liquor during extreme wet weather events.
- Filamentous and foaming organisms, their control and impact on population of desired organisms.
- Reestablishing the process after a significant wet weather/cold weather event.

What Strategies Are Appropriate for Bulking and Foaming?

The most effective strategy to deal with foaming is to eliminate the conditions that encourage the growth of nocardiaforms. However, this is not always easy because the exact cause-and-effect relationships have not been fully established.

Refer to Appendix A for a supplemental document describing this issue in detail. Also refer to Jenkins et al. (2004) for a comprehensive text on the subject.

What Are Final Clarifier Design and Operational Considerations?

Clarifier design is crucial to the successful operation of BNR facilities. This is particularly true when targeting low nitrogen and phosphorous levels because of the solids-associated nitrogen and phosphorous.

Several facilities have reported improved sludge settleability with the conversion to enhanced biological phosphorus (EBPR) removal. This may be attributed to storage products, such as glycogen and polyphosphate, which have reported densities of 1.25 – 1.29 g/mL (Ford et al. 1983), and 1.23 g/mL (Friedberg and Avigad 1968), respectively. These values are higher than the value of 1.04 –1.06 g/mL for the activated sludge (Dammel and Schroeder 1991). Nonetheless, due to the sensitivity of effluent TN and TP to effluent TSS levels, care must be taken in designing and operating final clarifiers. The following are some of the key elements:

- The resolubilization of phosphorus in the sludge blanket can lead to elevated effluent TP. This can be reduced by increasing the side water depth (SWD) of the clarifier so that the released phosphorus is more likely to exit with the underflow. Within limits, the RAS flow rate may be increased to prevent the phosphorous from migrating to the effluent overflow.
- Many EBPR facilities have a supplemental chemical feed system to enhance process reliability with the chemical being added to or just prior to the final clarifier. Clarifier design must consider the increased solids produced as a result of chemical phosphorous removal.
- Deep clarifier sludge blankets promote denitrification, which could result in poor settleability due to buoyancy caused by the released nitrogen gas. It can also result in secondary phosphorous release and higher SVI. These issues can be resolved by providing a clarifier SRT

of two to three days or less under average day conditions. In order to maintain a shallow sludge blanket of no more than 1 to 2 feet, a sludge collection mechanism with adequate capacity to withdraw sludge quickly should be provided. The use of clarifiers for sludge storage or for maximizing RAS thickening should be avoided.

- Maintaining a shallow sludge blanket will also provide sufficient space for the blanket to expand in response to wet weather conditions when a net transfer of solids occurs from the bioreactor to the clarifiers. If the clarifier cannot accommodate the increased solids, washout may result. Significant solids washout has multiple process impacts, including elevated effluent total solids, elevated effluent total phosphorus, and loss of nitrification.
- Even flow split to final clarifiers is critical for realizing the full capacity of the units provided. Poor performance of an overloaded clarifier generally cannot be compensated by good performance of an underloaded clarifier.

The following features are often included to improve clarifier performance:

- Full radius scum collection mechanism for more efficient removal of surface foam and scum
- Proper sludge collection mechanism (discussed above)
- Baffles
- Adequately sized flocculating well to promote bioaccumulation
- Energy dissipating inlets
- Stand by polymer feed system (particularly for wet weather solids control)

Stress testing and computational fluid dynamic models can be used to identify performance bottlenecks. More information on clarifier design, operation, and testing may be found in WEF MOP 29 (WEF and ASCE/EWRI 2005).

What Strategies Are Available for Managing Anaerobic Digestion Solids Dewatering Return Streams?

Streams from the sludge dewatering process (often called "centrate" as many wastewater treatment plants use a centrifuge for dewatering; also referred to as "reject water") generally contains high concentrations of nutrients. Because this topic involves varying characteristics of the stream and various treatment options, a separate discussion of this topic is posted as a separate document as Appendix B.

Bowden et al. 2015 provides comprehensive coverage of biological and physical/chemical sidestream treatment options. Other references include a text on biological short-cut nitrogen removal (WEF and WERF 2015) and a compendium on deammonification (WRF 2019e).

Anaerobic digestion processes and thermal hydrolysis digestion processes in particular can generate refractory soluble organic nitrogen (rSON), which is highly resistant to biological degradation. A WRRF's ability to meet low effluent nitrogen concentrations may be constrained by SON concentrations and affected by SON from anaerobic digestion processes. Refer to WRF 2019f for additional discussion on SON.

How Do You Determine Maintenance Requirements and Priorities?

There is a need to have a preventive and predictive maintenance program on all equipment if possible, particularly on mixers, recycle pumps, alternate carbon source pumps, and clarifiers. Whatever impacts permit limits is a priority including blowers, mixers, recycle pumps, alternate carbon storage and delivery system, and secondary clarifiers.

When Starting Up a New Plant or an Upgraded Plant, What Training Would Be Required for Operators, Process Engineers, and Maintenance Staff?

All staff needs to understand the theory of nutrient removal, the metabolic requirements of the organisms and their byproducts, and what process control parameters need to be monitored and how to optimize the process. They need training in the operation and an overview of maintenance on all equipment. The maintenance staff needs detailed and extensive training on electrical and mechanical needs of the equipment and lubrication and cleaning requirements. Operators and process engineers must be trained in proper sampling techniques and interpretation of data.

APPENDIX A

What Strategies Are Appropriate for Bulking and Foaming?

Text Developed by Sam Jeyanayagam, PhD, PE, BCEE; Malcolm Pirnie, Inc.

Introduction

Filamentous bulking and foaming are two major operating problems associated with biological nutrient removal (BNR) plants. They reduce treatment capacity, negatively impact effluent quality, and create serious housekeeping and odor problems. An in-depth examination of the topic may be found in Jenkins et al. (2004); Wanner (1994); and WEF (2005a). This section contains a brief discussion of the causes and potential corrective strategies of bulking and foaming in BNR systems.

Filamentous Bulking

The presence of some filamentous organisms provides a backbone to the floc structure, thus helping the sludge to settle in the final clarifiers, producing a clear effluent. Excessive filaments, however, are associated with poor settling sludge and high effluent t solids. A variety of operating conditions, singly or in combination, can cause the growth of filamentous organisms such as low DO, low or high F:M ratio, nutrient deficiency, sulfides, and low pH values. Table 1 lists the commonly encountered filaments and the causative factors (Jenkins et al. 2004).

Table 1 - Filament Types and Causative Agents

Cause	Filamentous Organism
Low DO Concentration	S. *natans*; Type 1701; H. *hydrossis*
Low F/M	Types 0041, 0675, 1851, and 0803
High Levels of Low Molecular Weight Organic Acids	*Thiothrix* I and II; N. *limicola* I, II, and III; Types 021N, 0914, 0411, 0961, 0581, and 0092
Hydrogen Sulfide	*Thiothrix* I and II; *Baggiatoa* spp.; Types 021N and 0914
Nitrogen Deficiency	*Thiothrix* I and II
Phosphorus Deficiency	N. *limicola* III; H. *hydrossis*; and S. *natans*
Low pH	Fungi

Source: Jenkins et al. 2004

Filament identification is the first step in resolving the problem. In general, operational controls focus on removing the conditions responsible for bulking or killing filamentous organisms to control their number. Some common strategies include:

- Use of selectors to provide growth advantage to floc formers
- Return activated sludge (RAS) chlorination
- Nutrient addition
- Correcting the DO concentration in the bioreactor
- Correcting the pH

Filamentous Foaming

While *Nocardi*a sp is the most commonly found organism responsible for filamentous foaming, others (such as *Microthrix parvicella* and Type 1863) can also cause foaming. Because many of the organisms that cause foaming look similar, the term "nocardiaforms" is used to refer to them collectively.

The presence of some foam in the activated sludge bioreactor is normal. In a well operated process, 10 to 25 percent of the bioreactor surface will be covered with 50 to 80 mm (2 to 3 in) layer of light tan foam. Under certain operating conditions foam can become excessive and affect operations.

Three general types of problem causing foams are: stiff white foam, brown/dark tan foam often incorporating scum, and very dark brown or black foam. If stiff white foam is allowed to accumulate, it can be blown by wind onto walkways and create hazardous working conditions. It can also create an unsightly appearance, odors, and transmit pathogens. If greasy or thick scummy foam builds up and is conveyed to the secondary clarifiers, it will tend to build up behind the influent baffles and create additional cleaning requirements. It can also plug the scum removal system.

Foaming is typically associated with warmer temperatures, grease, oil, fats, and long SRTs. Because foaming is a surface phenomenon, it typically has a longer SRT than the underlying MLSS. Plants prone to foaming often receive oil and grease waste (from restaurants without or with poorly performing grease traps), have poor or no primary scum removal, recycle scum, and have bioreactors and final clarifiers that are not properly designed to remove scum and foam.

The most effective strategy to deal with foaming is to eliminate conditions that encourage growth of nocardiaforms. However, this is not always easy because exact cause-and-effect relationships have not been fully established. The following is a listing of foam and scum control methods that have been implemented in BNR systems:

- Allow free-flow surface foam and scum in bioreactors. Eliminate dead ends, sharp corners, and quiescent zones in channels or bioreactors where there is a potential for foam and scum to accumulate.
- Selective surface wasting for the preferential removal of foam and scum. Collected foam should not be recycled.
- Design secondary sedimentation tank inlet wells and flocculation wells to allow for the passage of floating material.
- Install an effective scum removal system on secondary sedimentation tanks, preferably a full radius skimmer.
- Install chlorine (0.5 to 1 percent solution) sprays at localized points of foam and scum collection and/or accumulation to kill nocardiaforms.
- Consider adding polymers to destroy the foam's hydrophobic properties, allowing it to mix with the sludge so that it can be removed with the waste sludge.
- Use of anoxic selectors
- Use of water spray to breakup foam
- Use of antifoaming agents
- Reduce aeration

APPENDIX B

What Strategies Are Available for Managing Streams from Sludge Operations?

Text Developed by Sam Jeyanayagam, PhD, PE, BCEE; Malcolm Pirnie, Inc.

Issue

At nutrient removal plants, the return streams from sludge operations (e.g., dewatering) are of particular concern. The quantity and quality of these streams vary based on the technology used in the solids processing operations. For example, anaerobic digestion is likely to release more phosphorus than aerobic digestion. Likewise, sludge thickening using belt filter dewatering generally generates two times more recycle flow (filtrate) compared to centrifuge dewatering because of the amount of wash-water used in the dewatering operation. Total recycle streams can amount to 20 to 30 percent of the plant influent.

The use of anaerobic digesters is of particular concern at nutrient removal facilities. The recycle stream from anaerobically digested sludge dewatering operation can contain as high as 900 to 1,100 mg/L of ammonia and 100 to 800 mg/L of phosphorus. The complex microbial consortium in a single sludge system has a limited ability to quickly respond to influent variations by self-adjusting itself. The period of acclimation is directly influenced by MCRT, MLSS, and the magnitude and duration of peak loads. Within limits, higher MCRT and MLSS enhance microbial diversity and system robustness, while extremely high and persistent loadings can be catastrophic.

Every nutrient removal plant must have a plan for managing recycle loads. This section outlines some of the strategies available for managing recycle loads.

Equalization

Return streams often occur intermittently in many facilities, causing significant variation in nutrient loadings as well as significant short term peak loads that could overwhelm the biological process. For example, if dewatering operations occur over one shift, five days per week, the recycle loading could potentially be four times the loading generated by a 24/7 operation.

The simplest method to eliminate intermittent short-term loadings is to store recycle stream and return to the mainstream process at a controlled rate or during reduced wastewater loading periods, such as evenings and weekends. Alternatively, sludge operations can be rescheduled for the night shift to even out the recycle loading.

Ammonia and Nitrogen Removal Technologies

A number of innovative approaches to biological treatment of the recycle stream for ammonia or total nitrogen removal have been developed in recent years. These strategies use the following basic processes either singly or in combination:

- Oxidation of ammonia to nitrite (nitritation)
- Reduction of nitrite to dinitrogen gas (denitritation)
- Oxidation of ammonia to nitrate through nitrite (nitrification)
- Anaerobic oxidation of ammonia to dinitrogen gas (deammonification).

Some of the processes also provide the benefit of supplying a source nitrifying biomass to the main-stream process (bioaugmentation). A brief description of each technology is provided below. The features of the various technologies are summarized in Table 1.

Nitritation/Denitritation Processes

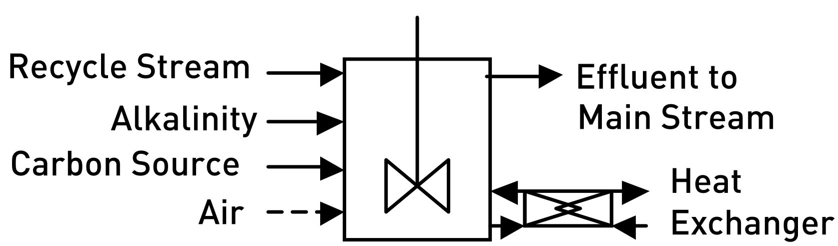
SHARON (Single Reactor High Activity Removal Over Nitrite)

SHARON is one of the first technologies of the current generation of side-stream treatment processes to be developed and, thus, has the longest track record. A schematic of the process is shown in Figure 1. Distinguishing features of the process are as follows:

- Elevated recycle stream temperature inhibits nitrite oxidation
- Once-through process – no sludge retention
- Insulated/heated reactor
- Denitritation to dinitrogen gas with methanol addition
- SRT of 1 – 2 days
- One reactor with cycling of air or two separate reactors

Full-scale SHARON reactors are operating at Zwolle, Beverwijk, and Groningen in the Netherlands. Two more projects have been designed: one for Haag in the Netherlands and the other for the Wards Island WPCP in New York City.

Figure 1 - SHARON Process Schematic

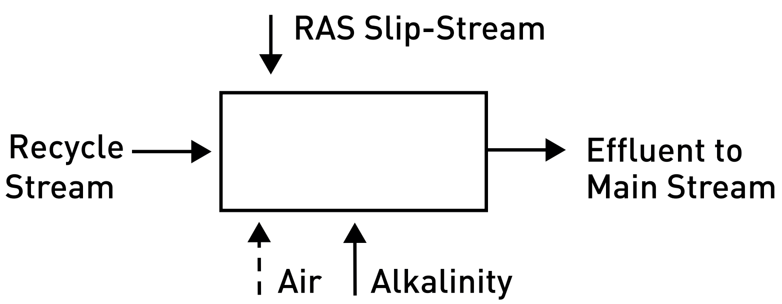


AT-3

This process utilizes a slip-stream of RAS biomass to oxidize ammonia in the recycle stream to nitrite. A schematic of the process is shown in Figure 2. Distinguishing features of the process are as follows:

- Free ammonia and nitrous acid toxicity inhibits nitrite oxidation
- Once-through process - no sludge retention
- Open tank
- Potential for bioaugmentation
- SRT of 1 – 3 days
- Can be modified for denitritation to dinitrogen gas (MAUREEN)

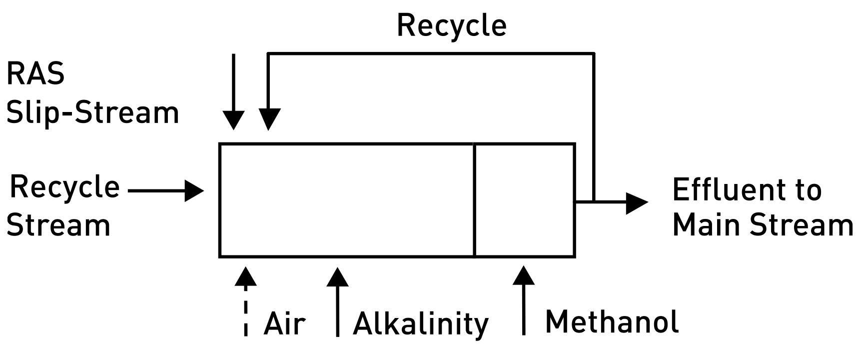
Figure 2 - AT-3 Process Schematic



MAUREEN (Mainstream Autotrophic Recycle Enabling Enhanced N Removal)

MAUREEN is a modified version of AT-3 that incorporates an anoxic compartment for denitritation and solids retention through recycle of effluent biomass from the end of the tank to the beginning of the tank. Methanol is required as a source of organic carbon. A schematic of the process is shown in Figure 3.

Figure 3 - MAUREEN Process Schematic



STRASS

The STRASS process is a sequencing batch reactor (SBR) nitritation process that utilizes pH control to inhibit nitrite oxidation. Distinguishing features of the STRASS process are as follows:

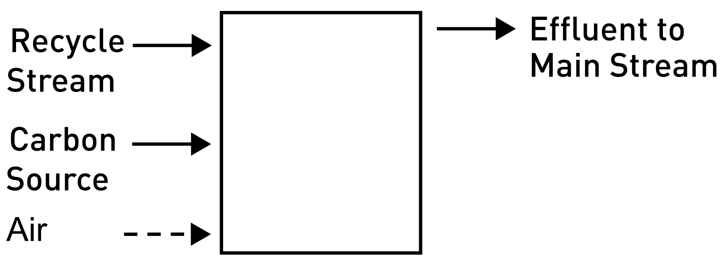
- pH control, low dissolved oxygen to inhibit nitrite oxidation
- Sludge retention (sequencing batch reactor)
- High SRT
- External carbon source (primary sludge)

The STRASS process is named for Strass, Austria where the process was first utilized full-scale. Salzburg, Austria is the other full-scale operation. The Strass operation has been converted to the DEMON process. The process has been piloted by the Alexandria, Virginia Sanitation Authority in the United States.

Submerged Attached Growth Bioreactor (SAGB)

The SAGB is a single-unit, single-zone submerged attached growth bioreactor with intermittent aeration and external carbon addition. A schematic of the process is shown in Figure 4.

Figure 4 - SAGB Process Schematic



Operating experience is limited to a single pilot-scale evaluation at the Deer Island WWTP in Massachusetts, USA.

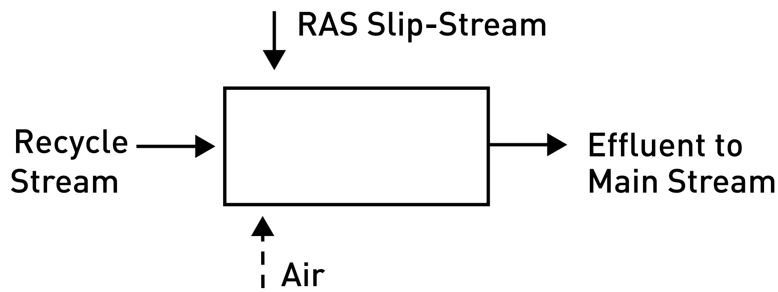
Nitrification

BABE (Bioaugmentation Batch Enhanced)

BABE was developed in the Netherlands by DHV in association with Delft University of Technology. Recycle stream from sludge digestion is mixed with return activated sludge and is reacted in a batch mode. Distinguishing features of the process are as follows:

- Sludge retention (sequencing batch reactor)
- Potential for bioaugmentation
- SRT < 1 day

Figure 5 - BABE Process Schematic



BABE was recently demonstrated full-scale at Garmerwolde WWTP in the Netherlands.

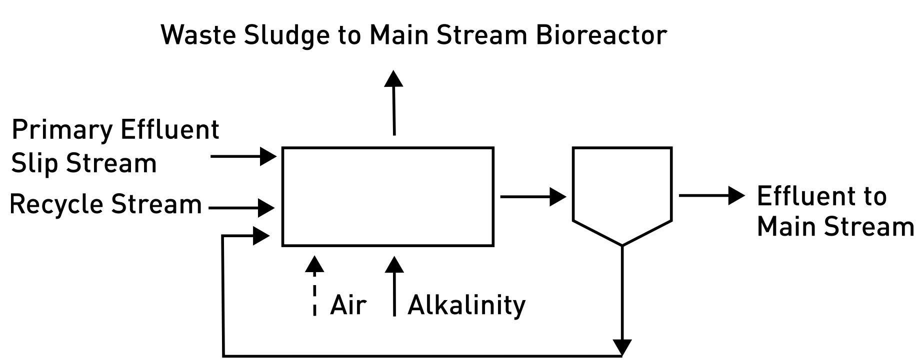
In-Nitri (Inexpensive Nitrification)

In-Nitri is a side-stream activated sludge system. Recycle stream ammonia is oxidized to nitrate. Sludge is wasted to main-stream treatment for a bioaugmentation effect. A slip-stream of primary effluent is blended in to acclimate side-stream bacteria to the main-stream. A schematic of this process is shown in Figure 4. Distinguishing features of the process are as follows:

- Sludge retention (clarifier)
- Potential for bioaugmentation

There are no full-scale demonstrations of this technology.

Figure 6 - In-Nitri Process Schematic



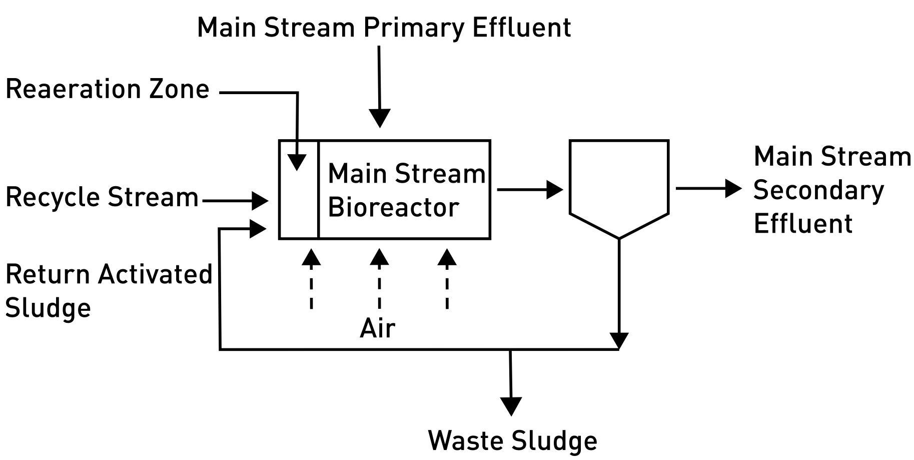
BAR (Bioaugmentation Regeneration/Reaeration)

The BAR process incorporates the discharge of recycle stream into the sludge reaeration zone of the main-stream bioreactor. The stream is fully nitrified by endogenous nitrifiers, which are then carried forward to charge the main aeration tank, thereby reducing the SRT required for complete nitrification. A schematic of this process is shown in Figure 5. Distinguishing features of the process are as follows:

- Once-through process - no sludge retention
- Potential for bioaugmentation

The process has seen very wide use in the Czech Republic. The technology was also developed independently in for Appleton, Wisconsin, USA.

Figure 7 - BAR Process Schematic



R-DN (Regeneration Denitrification)
R-DN is identical to the BAR process.

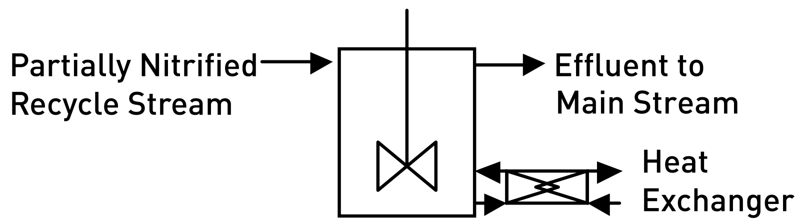
Deammonification

ANAMMOX (Anaerobic Ammonia Oxidation)
Ammonia and nitrite in equimolar concentrations can be oxidized to dinitrogen gas anaerobically by bacteria in phylum planctomycetes. An anammox reactor can be coupled with a SHARON reactor to provide feed with the required ammonia and nitrite proportions. A schematic of the process is shown in Figure 6. Distinguishing features of the process are as follows:

- Autotrophic – no external carbon source required
- Anaerobic – no aeration required
- Heated/insulated reactor (T = 30°C-35°C)
- Sludge retention (sequencing batch reactor)
- DRT of 30-50 days
- Requires pre-treatment of feed to equimolar concentration of ammonia and nitrite

A full-scale anammox reactor coupled to a SHARON process is operating in the Netherlands.

Figure 8 - Anammox Process Schematic



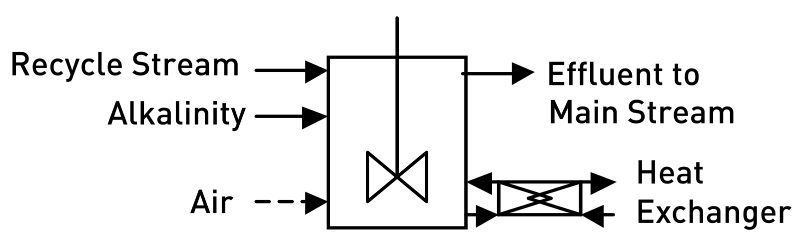
DEMON (DeAmmonification)

DEMON incorporates partial aerobic oxidation of ammonia to nitrite and anaerobic oxidation of ammonia and nitrite to dinitrogen gas by the anammox reaction in a single-sludge process. A schematic of this process is shown in Figure 7. Distinguishing features of the process are as follows:

- Intermittent aeration to control nitrite oxidation
- Sludge retention (sequencing batch reactor)
- Suspended growth
- Autotrophic denitritation – no external carbon required

DEMON has been demonstrated full-scale at Strass, Austria.

Figure 9 - DEMON Process Schematic



CANON (Completely Autotrophic Nitrogen Removal Over Nitrite)

Similar to DEMON except with attached growth using floating plastic rings. Distinguishing features of the process are as follows:

- Oxygen limitation through biofilm controls nitrite oxidation
- Sludge retention (sequencing batch reactor)
- Attached growth (floating media)
- Experience with this technology is limited to laboratory-scale demonstrations

OLAND (Oxygen Limited Aerobic Nitrification-Denitrification)
OLAND is a two-stage membrane bioreactor process. Distinguishing features of the process are as follows:

- Oxygen limitation through biofilm controls nitrite oxidation
- Sludge retention (membrane bioreactor)
- Attached growth (floating media)

Experience with this technology is limited to laboratory-scale demonstrations.

Phosphorus Removal Technologies

Anaerobic digestion will cause biomass to release accumulated phosphorus. This is of particular concern for treatment facilities that utilize enhanced biological phosphorus removal (EBPR) because the recycle loading can reduce overall treatment efficiency. In addition, digester liquor typically contains elevated concentrations of ammonia and phosphorus, as well as adequate amounts of magnesium to form struvite, also known as magnesium ammonium phosphate ($MgNH_4PO_4$) under optimum pH conditions. Struvite tends to scale pipes, pumps, and centrifuges where turbulence drives out carbon dioxide, thereby raising the pH into the range conducive for struvite formation.

Treatment strategies to remove phosphorus from recycle streams entail:

Chemical Precipitation

Removal of soluble phosphorous with iron or aluminum salts. The inorganic precipitate is removed along with other settleable solids in the main-stream clarifiers.

Phosphorus Recovery

Struvite formation chemistry is used by Ostara Technologies Inc. to recover phosphorous and ammonia in recycle streams by forcing struvite precipitation under control condition in a proprietary up-flow fluidized bed reactor. Struvite is harvested as granules and marketed as a slow-release fertilizer under the trade name Crystal Green™.

Table 1 - Summary of Biological Treatment Technologies For Recycle Nitrogen Loading Management

Process	Full Scale	Ammonia Removal			Nitrogen Removal		Bioaugmentation		Configuration		
		Aerobic		Anaerobic					Suspended Growth		Attached Growth
		Nitritation $NH_3 \rightarrow NO_2$	Nitrification $NH_3 \rightarrow NO_3$	$NH_3 \rightarrow N_2$	Denitritation $NO_2 \rightarrow N_2$	Denitritation Mode (C Source)	In situ	External	Solids Retention (mode)	Chemo-stat	
Nitritation/Denitritation Processes											
SHARON	•	•			•	H (methanol)				•	
AT-3	•	•					•			•	
MAUREEN		•			•	H (methanol)	•		• (Recycle)		
STRASS	•	•			•	H (primary sludge)			• (SBR)		
SAGB		•			•	H (methanol)					•
Nitrification Processes											
BABE	•		•				•		• (SBR)		
In-Nitri			•					•	• (Clarifier)		
BAR/R-DN	•		•				•			•	
Deammonification Processes											
ANAMOX	•			•	•	A (air)			• (SBR)		
DEMON	•	•		•	•	A (air)			• (SBR)		
CANON		•		•	•	A (air)					•
OLAND		•		•	•	A (air)					•

H = Heterotrophic, A = Autotrophic

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