HIGH PURITY OXYGEN

BIOLOGICAL NUTRIENT REMOVAL (BNR)

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ABSTRACT

Since 1970 there have been nearly 300 high purity oxygen (HPO) activated sludge systems constructed worldwide both in industrial and municipal applications. With an increased focus of State and Federal regulations on nutrient removal, this paper provides a technology update of the high purity oxygen process for nutrient removal. This update will include experience, and actual operating performance data, from plants operating for more than twenty years in addition to current generation design concepts for optimization of the high purity oxygen process for full biological nutrient removal (BNR).

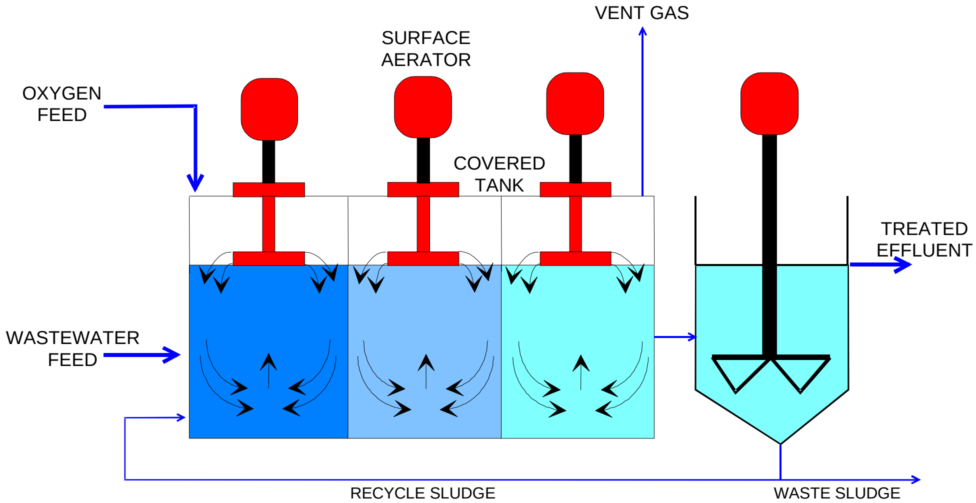
Conventional design for high purity oxygen systems for nitrogen removal has been employed for over twenty years, incorporating either single or two step design dependent on wastestream characteristics. Current generation high purity oxygen BNR design incorporates anaerobic stage(s) for biological phosphorus removal, anoxic stage(s) for denitrification, and selector technology. Further optimization, dependent on effluent permit limitations, includes multiple anoxic stages for denitrification polishing. Since biological processes for nitrification prefer neutral pH conditions, current generation design also incorporates an open stage stripping CO_2 for pH elevation. Increased pH, combined with the ability to efficiently operate at high dissolved oxygen concentration and high MLSS level, provide specific economic and operational advantages of the HPO-BNR System.

Operating data will be presented from several high purity oxygen nutrient removal plants and provide a comparison of current generation design approach versus effluent performance, and applicability of the HPO-BNR process as a stand alone treatment system or for efficient retrofit or conversion of existing systems.

HISTORICAL BACKGROUND

The HPO activated sludge process was developed and commercialized by Union Carbide (Linde Division). The initial full scale pilot program sponsored by the Federal Water Quality Administration (predecessor to the Environmental Protection Agency), EPA, was performed at a municipal plant in Batavia, NY from late 1968 and completed in 1970. In 1970, Union Carbide began commercialization of this process called which they called the UNOX® system. A simplified schematic of the system is shown in Figure 1. **(See Figure 1 "UNOX® Schematic Diagram")**

FIGURE 1
UNOX® Schematic Diagram



After more than a decade of successful commercialization of the HPO system the technology was acquired by Lotepro in 1981. Currently of the more than 110 operating HPO systems in municipal service in North America, approximately 1 in every 6 were designed for biological nutrient removal.

In 1997 Lotepro acquired a license to apply the A/O® system technology for biological removal of nutrients. The incorporation of the A/O® technology into the HPO design now allows Lotepro to offer an oxygen based treatment system applicable for complete BNR.

THE NEED FOR NUTRIENT REMOVAL IN WASTEWATER TREATMENT

The need to control the point source discharge of nutrients (both phosphorus and nitrogen) from municipal wastewater plant effluents prior to receiving waters has been recognized and studied for at least the past 2 decades. The basic reasoning behind incorporating nutrient removal can be summarized as follows:

Nitrogen

- Nitrogen in the form of unionized ammonia (NH_3-N) has toxicity effects to aquatic life. The fraction of unionized NH_3-N in water increases with increasing temperature and pH.

- NH_3-N discharged into the receiving stream will undergo the process of oxidation in the presence of dissolved oxygen and bacteria as shown below: This will cause a depletion in receiving water DO which is available to sustain the aquatic life.

$$NH_3 + H_2O \rightarrow NH^{+}_4 + OH$$

$$NH^{+}_4 + O_2 \xrightarrow[\text{Bacteria}]{\text{Nitrosomonas}} NO_2 + O_2 \xrightarrow[\text{Bacteria}]{\text{Nitrobacter}} NO_3$$

- The discharge of NO_3-N (nitrate) will contribute to the growth of algae in receiving waters, potentially leading to associated problems of DO depletion, algae blooms and odors. Discharge of nitrate and nitrite (NO_2-N) also become a concern if the receiving stream is to be used further downstream as a source for drinking water. The safe drinking water act (SDWA) amendments of 1986 require a maximum contaminant levels (MCL) for total nitrate and nitrite nitrogen of <10 mg/l. These are the primary reasons for providing in-plant denitrification prior to discharge to receiving water.

Phosphorus

- Phosphorus has also been observed to be the cause of excessive plant growth in receiving streams leading to both aesthetic problems from algae blooms, odors and DO depletion.

ASPECTS OF CONVENTIONAL HIGH PURITY OXYGEN SYSTEM DESIGN

In the text which follows the words “conventional” and “current generation” will be used in describing the HPO system. The conventional HPO system refers to that originally invented by Union Carbide which was primarily applied for removal of BOD and nitrification of wastewater. The current generation HPO system refers to the system as it now has evolved to incorporate complete biological nutrient removal.

The conventional system is an activated sludge process which is fed from a pure oxygen gas stream (instead of air) to accomplish secondary level biological wastewater treatment in an enclosed bioreactor followed by a clarifier. The ability of the system to maintain high dissolved oxygen concentrations in the mixed liquor, and the ability to match the oxygen demand of the wastewater by staging of the reactor, allows the system to be suitable for a variety of wastewater treatment applications.

Typical applications of the system for BOD removal or nitrification are:

- for medium to high strength wastewater (BOD typically 100 mg/l to >1000mg/l),
- for site locations with limited site area for new construction

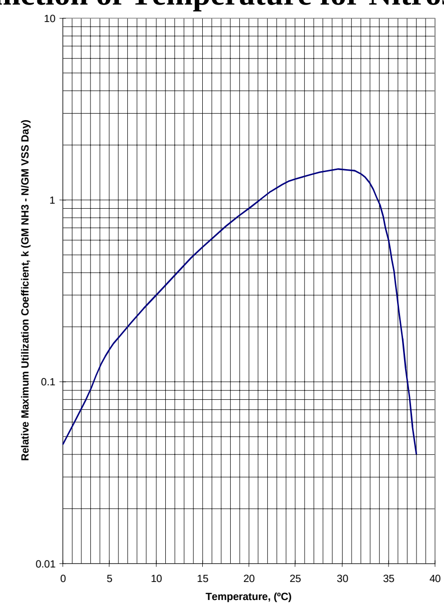
- for locations concerned with aesthetics, control of odors and control of noise generation

The following environmental design factors are considered critical to the proper design of any activated sludge process, including an HPO system and in particular a nitrification system.

1. Temperature
2. Dissolved oxygen
3. pH and alkalinity
4. Substrate levels
5. Inhibitory or toxic materials

Temperature
The net growth rate of the nitrifying organisms is dependent on temperature. Literature and laboratory studies indicate the applicable range of temperature for nitrification to be about 5-30 C. Figure 2 provides the typical relationship of temperature to nitrifying organism growth rate. **(See Figure 2 "Maximum Ammonia Nitrogen Utilization Coefficient, k, as a Function of Temperature for Nitrosomonas")**

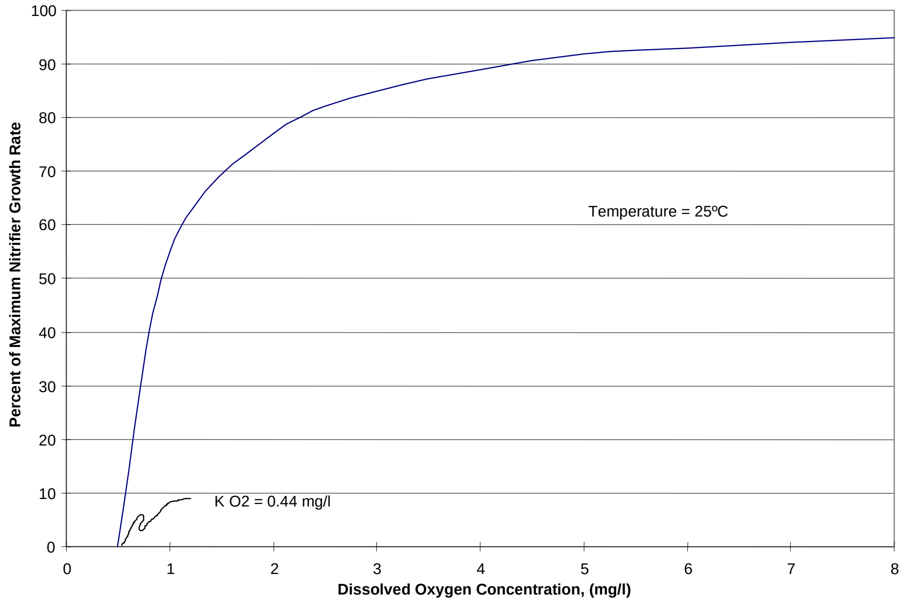
FIGURE 2
Maximum Ammonia Nitrogen Utilization Coefficient, k, as a Function of Temperature for Nitrosomonas



Dissolved Oxygen
The dissolved oxygen (DO) level is also a critical design factor for any activated sludge system. The effect of DO on the nitrification rate is shown in Figure 3. **(See Figure 3 "Effect of Dissolved Oxygen on the Growth Rate of Nitrifiers")** It indicates that lower DO's (in the range of 2 -3 mg/l) result in a nitrifier growth rate of about 60-70 % of the maximum attainable rate. The relationship is asymptotic and is predicted to achieve

about 85% of the maximum rate at DO's > about 6 mg/l. The basic design of an HPO system uses a design value of at least 6.0 mg/l to take advantage of this effect.

FIGURE 3
Effect of Dissolved Oxygen on the Growth Rate of Nitrifiers



pH and Alkalinity

The water chemistry balance in an HPO activated sludge system is more complex than a open air activated sludge system. This is due to the fact that carbon dioxide produced in the reactor during the biological oxidation process does not leave the process until the last reactor stage. The concentration of CO_2 dissolved in the mixed liquor, or in the gas space, is dependent on Henry's Law.

The equilibrium relationship between pH, alkalinity and % CO_2 in the gas phase for water at 1 atm is predicted based on the following equation for any reactor stage:

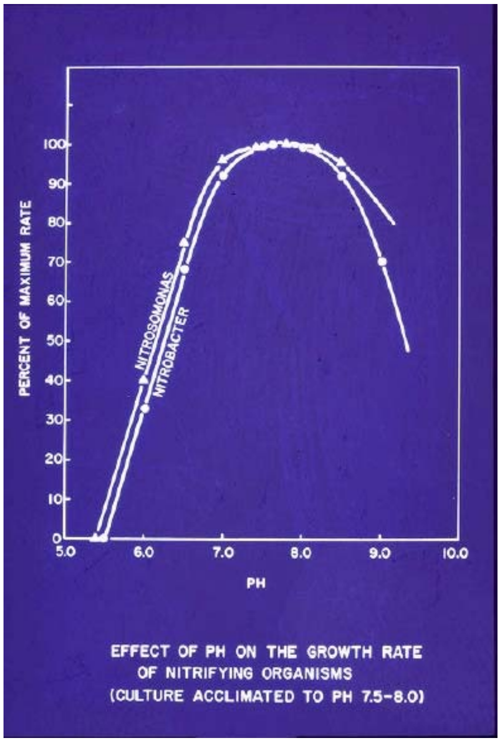
$$ALK\ (mg/l) = [CO_2] \times K_1/10^{-pH} \times {}^{50}/_{44}$$

Where

- ALK = alkalinity, mg/l as $CaCO_3$
- $[CO_2]$ = dissolved carbon dioxide, mg/l
- K_1 = bicarbonate dissociation constant at given water temp.

The relationship is of primary importance in HPO nitrification systems because of the reduced pH effect on nitrifier growth rate and SRT, the sludge retention time. The typical relationship showing the effect of pH on the growth rate of nitrifying organisms is shown in Figure 4. **(See Figure 4 "Effect of pH on Growth Rate")**

Figure 4
Effect of pH on Growth Rate



Substrate removal
The design effluent ammonia level used in a design is dependent on a plant's discharge permit.

Inhibitory materials in wastewater
The growth rate of nitrifier organisms can be retarded due to substances in the wastewater. These are typically heavy metals and organic compounds which may be either biologically degradable or undegradable by the mixed liquor organisms. The presence of these materials will impact the type of system (single or two step design) selected.

Definition of SRT
In consideration of the above design factors, a minimum critical SRT calculation was developed for use in establishing nitrification tank size which takes the form:

$SRTmin = (K_s + S)/(u_n \times S \times f_{pH} \times f_{DO})$

where

- S = effluent NH_3-N concentration, mg/l
- K_s = 1/2 saturation constant for Nitrosomonas bacteria
- u_n = maximum specific growth rate of Nitrosomonas bacteria
- f_{pH} = function to correct for reduced pH
- f_{DO} = function to correct for reduced DO

The above form of the SRT calculation for an HPO is system similar to the EPA's design procedure except for the application of the additional design parameters f_{pH} and f_{DO}.

For nitrification the HPO process can be applied as either a single or two step system. The design selection criteria for these HPO systems is given in Table 1. **(See Table 1 "Characteristics of Single and Two Step Nitrification")**

Table 1
CHARACTERISTICS OF SINGLE AND TWO STEP NITRIFICATION

Parameter	Single Step Nitrification	Two Step Nitrification
Applicability:	1) Low strength wastes (i.e. BOD <200 mg/l) (No toxics)	1) High strength (typical) wastes
	2) Where only seasonal or warm weather nitrification is required	2) Year round nitrification
Design Considerations:	1) Low F/M operation	1) High F/M operation - 1st step Low F/M operation - 2nd step
	2) Relatively long retention time	2) Generally reduced retention time
Operating Characteristics:	1) Reduced sludge production	1) Greater sludge production
	2) Increased oxygen consumption	2) Reduced oxygen consumption
	3) Reduced resistance to toxic materials and organic surges	3) Greater resistance to toxic materials and organic surges

A listing of currently operating HPO-BNR systems given in Table 2 indicates more than half are two step systems. The most recent plants have been designed as single step. **(See Table 2 Operating High Purity Oxygen Based Biological Nutrient Removal Systems")** The majority utilize the conventional HPO process having covered reactors. The remaining are current generation design and will be discussed further on in this paper.

Table 2
OPERATING HIGH PURITY OXYGEN BASED
BIOLOGICAL NUTRIENT REMOVAL SYSTEMS

Location	Flow MGD	Design	Biological Process
Amherst, NY	24	2 step	Nitrification
Syracuse NY OCSD Baldwinsville Plant	10	2 step	Nitrification
Baltimore, MD	70	--	Future Nitrification + P_R and Denitrification
Cedar Rapids, IA	45	1 or 2 step	Nitrification
Concord, NC CCSWA	33	2 step	Nitrification + future Denitrification
Rocky River Plant		1 step	Change to 1 step in 2003
Glen Ellyn, IL	15	2 step	Nitrification
Hagerstown, MD	9	1 step	Nitrification + P_R and Denitrification
Houston, TX 69th Street Plant	200	2 step	Nitrification
Indianapolis, IN Belmont Plant	--	1 step	Nitrification
Lancaster, PA	21	1step	BOD, P_R + future nitrification/denitrification
Madisonville, KY	5	2 step	Nitrification
Mineral Ridge, OH Mahoning County Plant	4	2 step	Nitrification
Monterrey, Mexico	114	1 step	Nitrification
Morganton, NC	10.5	1 step	Nitrification + future Denitrification
Pensacola, FL	24	1 step	Nitrification + future Denitrification
Rochester, MN	19	2 step	Nitrification
Rocky Mount, NC	14	1step	Nitrification + P_R and Denitrification
Syracuse, NY OCSD Clay Plant	10	2 step	Nitrification
Tampa, FL	76.5	1 or 2 step	Nitrification + P_R and Denitrification

A two step or series HPO system requires intermediate clarification prior to nitrification.

Tampa, FL
An example of such a system is Tampa, FL. The HPO systems at Tampa treat primarily domestic wastewater with a component of brewery waste. Average operating data from the year 1996 is given in Table 3. **(See Table 3 Tampa FL Operating Data")** Monthly performance data for removal of BOD and TKN are given in Figure 5A and 5B. **(See Figure 5A "Tampa, FL 2 Step Nitrification 1996 Monthly Performance Data for Removal of BOD" and Figure 5B "Tampa, Fl 2 Step Nitrification 1996 Monthly Performance Data for Removal of TKN")**The characteristics of the system is a highly loaded first step designed for BOD removal only (low SRT condition). The first step acts to absorb any surges in organic loading allowing the second step to operate solely in the

nitrification mode. Design flexibility for a bypass of flow on the order of 5-10% is included to ensure the second step will be able to maintain an appropriate MLSS in the reactor. The second step is designed for essentially zero sludge production.

Table 3
TAMPA FL
OPERATING DATA

Carbonaceous Step	Design	1996 Average
Q, MGD	76.5	52.5
F/M, 1/day	1.66	3.25
RTQ, hrs.	0.9	1.2
MLSS, mg/l	4100	1600
BOD, mg/l	192	215
SRT, day	0.90	0.44
influent pH	7.3	7.3
influent T °C	18-30	27

Nitrification Step	Design	1996 Avg.
TKN, mg/l	22	30.4
RTQ, hr.	1.35	2.3
MLSS, mg/l	2900	1730
SRT, day	15.7	9.6
effluent pH	5.90	6.62

FIGURE 5A
Tampa, FL 2 Step Nitrification
1996 Monthly Performance Data for Removal of BOD

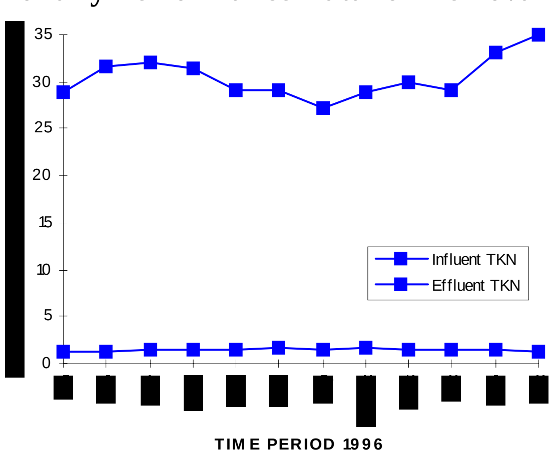
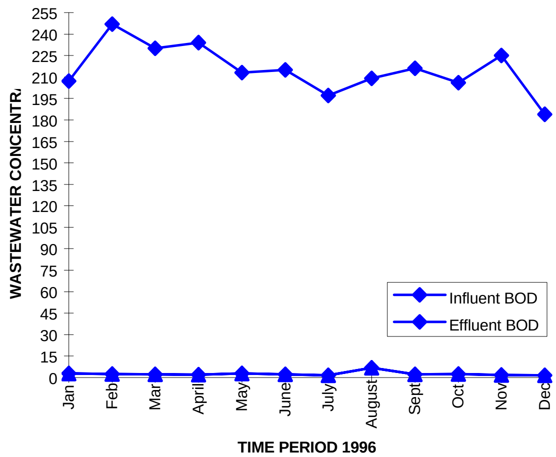


FIGURE 5B
Tampa, FL 2 Step Nitrification
1996 Monthly Performance Data for Removal of TKN



Hagerstown, MD

An example of a single step system is Hagerstown, MD, a 5 train, 3 stage reactor which was started up in 1981. Average operating data for the year 1996 is given in Table 4. **(See Table 4 "Hagerstown, MD")** Monthly performance data for removal of BOD and TKN are given in Figure 6A and 6B. **(See Figure 6A "Hagerstown, MD Single Step Nitrification 1996 Monthly Performance Data for Removal of BOD" and Figure 6B "Hagerstown, MD Single Step Nitrification 1996 Mothly Performance Data for Removal of TKN")** The effluent BOD and TKN averaged approximately 6 mg/l and 2 mg/l respectively over the time period.

Table 4
HAGERSTOWN, MD

	Design	1996 Average
Q, MGD	9.0	9.8
F/M, 1/day	0.22	0.28
RTQ, hrs.	4.4	4.2
BOD, mg/l	115	95
TKN, mg/l	40	23.6
T°C	13-24	15.9
SRT days	14.6	9.1
MLSS	4700	2450

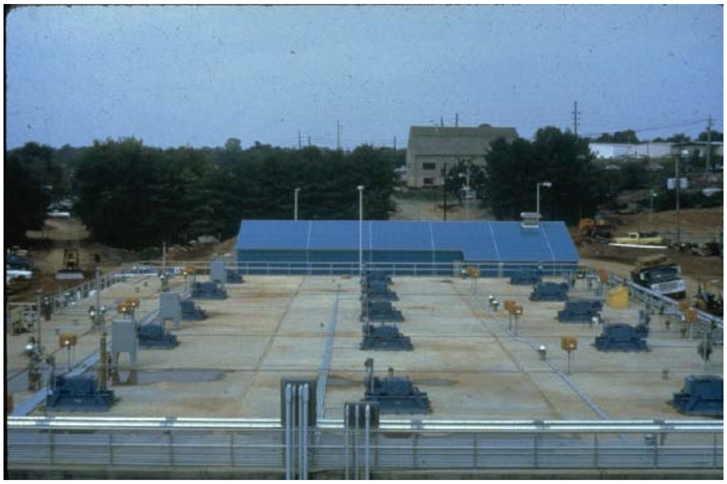


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Figure 6A
Hagerstown, MD Single Step Nitrification
1996 Monthly Performance Data for Removal of BOD

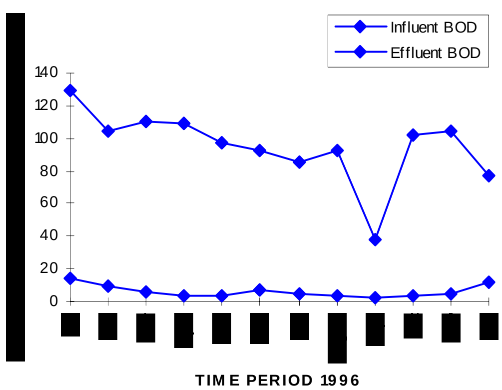
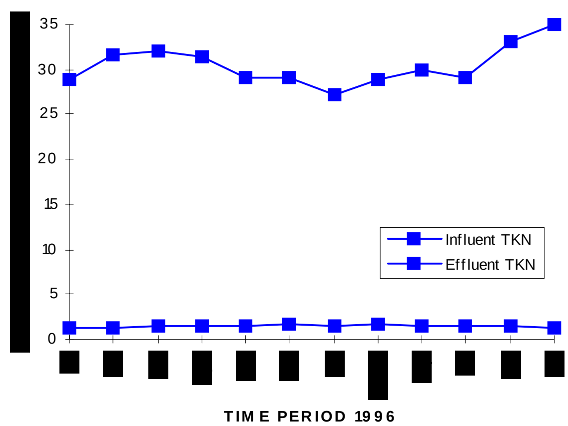


Figure 6B
Hagerstown, MD Single Step Nitrification
1996 Monthly Performance Data for Removal of TKN



ASPECTS OF CURRENT GENERATION HPO-BNR DESIGN

Requirements for removal of P and N from wastewater are site specific but speaking generally, may involve achieving effluent limits as follows:

<u>Phosphorus</u>
Total P < 2 mg/l
Soluble P ≤ 1 mg/l

<u>Nitrogen</u>
NH_3-N < 1 mg/l
Total N ≤ 9 mg/l
≤ 5 mg/l most stringent

ANAEROBIC ZONE

Historically, P has been removed by a physical precipitation process by adding Alum, ferric chloride or another metal salt to the wastewater. The goal of the HPO-BNR system is to eliminate the need for precipitation of P by incorporating an anaerobic zone within the HPO reactor. By exposing the mixed liquor to an alternate oxygen deficient then oxygen rich environment a selective mechanism to grow a class of phosphorus-removing bacteria is initiated. This mechanism is called Anaerobiosis. Laboratory and pilot study work have indicated the release of phosphorus from the biomass and soluble BOD absorption into the biomass occur simultaneously in the anaerobic zone.

The anaerobic zone of the reactor for an HPO system consists of 3 or 4 open tank compartments in series, each having a small center mounted mixer. Recycle sludge from the underflow of the secondary clarifier will provide the mixed liquor to this zone. Since the RAS may have a small amount of DO or chemically bound oxygen in the form of NO_3, the first compartment may actually operate as an anoxic compartment.

In addition to initiating the biological mechanism for P removal, the inclusion of the anaerobic zone prior to an aerobic reactor may additionally provide a mixed liquor environment which will not support filamentous type organisms (most typically identified as Nocardia). These organisms have historically led to poor secondary sludge settling, producing an unsightly biological foam at the clarifier surface in both air and oxygen activated sludge systems.

Several operating HPO systems (without P removal requirements) operate with an anaerobic first stage in an effort to limit growth of filamentous organisms. For example, South Essex Sewer District (Salem, MA) has been operating in this mode for about 1 year.

ANOXIC ZONE

Anoxic zones are used for plants requiring some level of total nitrogen removal. Anoxic denitrification is a process where chemically bound oxygen in the form of nitrate and nitrite is used by organisms as a source of oxygen for respiration. This phenomenon may occur in an aerated nitrification system if the dissolved oxygen in certain areas of the reactor becomes limiting to the organisms (i.e. 0-0.5 mg/l).

The anoxic zone for an HPO system is a separate reactor stage incorporated between the anaerobic stage (if required) and the aerobic stages. The nitrified effluent and mixed liquor (taken prior to clarification) is recycled to the anoxic zone with the amount of recycle flow proportional to the amount of denitrification required. The single anoxic zone will typically enable the HPO-BNR process to achieve an effluent total N $\leq$ 9 mg/l.

If a total effluent nitrogen limit $<$9 mg/l is required a secondary anoxic zone would be added. A process modification for enhancing the denitrification rate in the secondary anoxic zone without utilizing an external carbon source would also be incorporated in a current generator design. For an HPO-BNR system, the secondary anoxic zone would follow the oxygen reactor stages. Using dual anoxic zones a total effluent nitrogen level of $\leq$5 mg/l as N can be achieved.

pH Control

The conventional HPO system operates with an effluent pH which is less than an air system, tending to reduce nitrifier growth rate. To improve nitrifier growth rate, and also eliminate the need for chemical addition, current generation design incorporates an "open" intermediate or final stage in the HPO system. By exposing the mixed liquor to atmosphere, dissolved CO_2 will leave the system as a result of the aerator turbulence and mixing.

Incorporation of an open stage option in the HPO-BNR scheme has been observed by Lotepro to elevate the mixed liquor pH 0.4-0.6 units.

HPO BNR DESIGN APPROACH

A process schematic showing the current generation HPO system for biological nutrient removal is shown in Figure 7. **(See Figure 7 "UNOX BNR Systems Process Flow Schematic")** As shown, the core of the process remains oxygen based and includes options for:

- anaerobic zone (for P removal and selector)
- anoxic zones (single or dual for denitrification)
- open stage in HPO reactor (pH adjustment)

FIGURE 7
UNOX BNR Systems
Process Flow Schematic

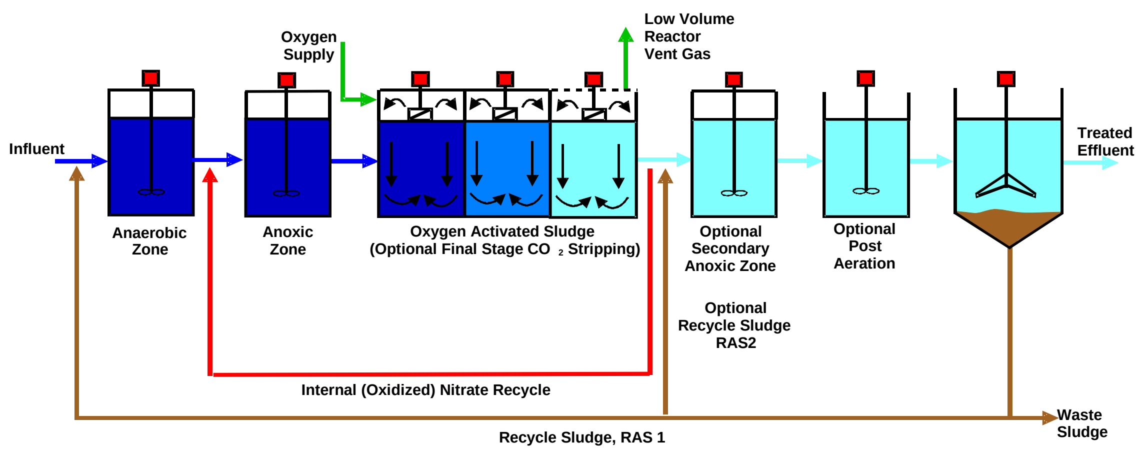


Table 5 provides typical design parameters for an HPO-BNR system. **(See Table 5 "Basic Design and Operating Parameters for a Current Generation HPO BNR System")**

Table 5
BASIC DESIGN AND OPERATING PARAMETERS FOR A CURRENT GENERATION HPO BNR SYSTEM

Basin Configuration	Staged Cells
Number of Stages	
Anaerobic	3 or 4 compartments
Anoxic	1 or 2
HPO	3 or 4
Retention Time, Hr.	
Anaerobic	0.5-1
Anoxic	0.5-1
HPO (BOD removal)	1-2
HPO (Nitrification)	2-6
Biomass Loading lb BOD/lb MLVSS-D	0.15-1.5
BOD_5/P ratio	$\geq$10
MLSS mg/l	2000-6000
Temperature, °C	5-35

Lancaster, PA

An example of a grassroots HPO-BNR system is Lancaster, PA (North plant). The treatment process utilizes an initial anaerobic zone followed by HPO to treat primary clarified wastewater for BOD, nitrification and P removal in a single step. The HPO reactors incorporate an open third stage for CO_2 stripping.

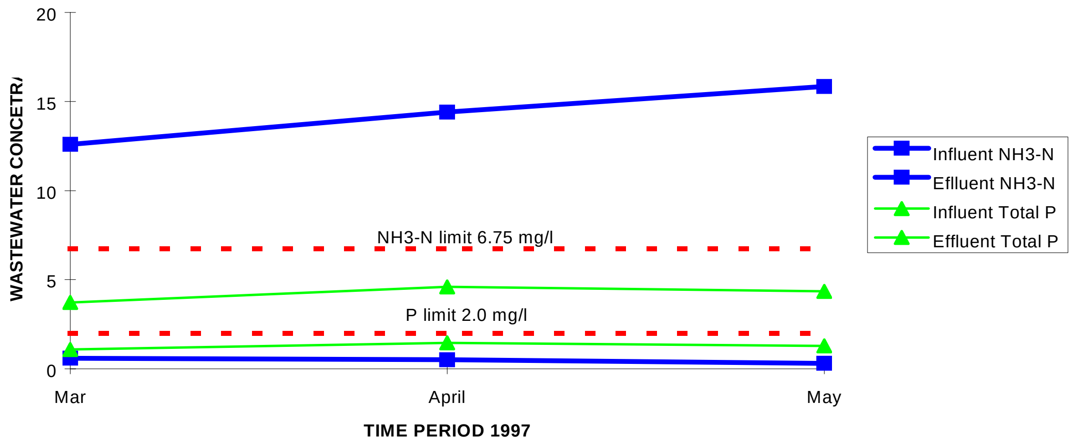
Lancaster is required to meet an effluent level of total P of 2.0 mg/l. The required level of treatment for NH_3-N is seasonal, 6.75 mg/l in the winter and 2.25 mg/l in the summer.

Performance data obtained for a 3 month period in winter - spring 1997 is shown in Figure 8 and indicates consistent effluent permit compliance for NH_3-N and P. **(See Figure 8 "Lancaster, PA Performance Data for Removal of NH_3-N and Total P")**

Lancaster, PA (North Plant in foreground)

Figure 8

Lancaster, PA Performance Data for Removal of NH_3-N and Total P



Morganton, NC

An example of an operating HPO-BNR system process designed for nitrification and CO_2 stripping, is Morganton, NC. The Morganton plant treats a municipal wastewater with an industrial component from a textile production facility. The plant was originally designed with 2 train, 4 stage conventional system for BOD removal.

The recent expansion of the plant from 7 to 10.5 MGD capacity required seasonal nitrification (April to October). The existing system was converted to operate as a single sludge nitrification reactor including removing a large portion of the reactor cover in stage 3 to allow stripping of dissolved CO_2. A third train was also added. The configuration of the third train also included the provision to add an anaerobic/anoxic zone in the future. Figure 9A shows the original and converted reactor configuration of the existing 2 trains. **(See Figure 9A Reactor Modifications, Morganton, SC")** Figure 9B shows the new third train. **(See Figure 9B "New Reactor No. 3, Morganton, SC")**

Figure 9A

Reactor Modifications, Morganton, NC

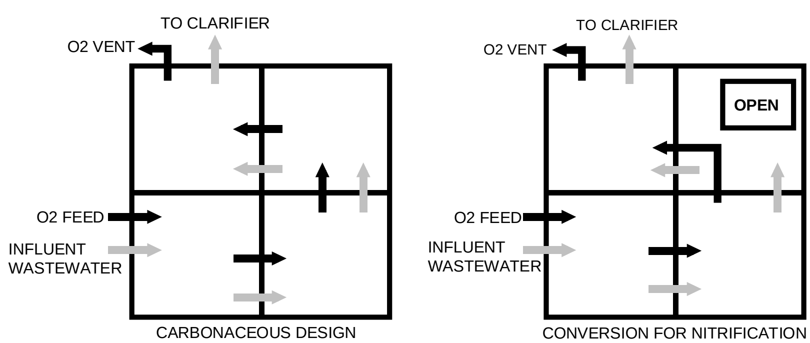
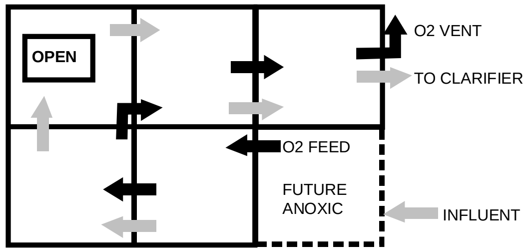


Figure 9B
New Reactor No. 3, Morganton, NC



Data collected during a performance test in November 1997 is given in Figure 9C. **(See Figure 9C "Morganton, NC Stagewise pH Performance Test 11/11-11/14/97")** The data illustrates the CO_2 stripping effect and subsequent pH elevation due to open stage No. 3. Monthly performance data from 1997-1998 for removal of NH_3-N is given in Figure 9D, indicating consistent permit compliance. **(See Figure 9D "Morganton, NC Monthly Performance Data for Removal of NH_3-N")**

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Morganton, NC Third HPO-BNR Train

Figure 9C

Morganton, NC Stagewise pH
Performance Test 11/11-11/14/97

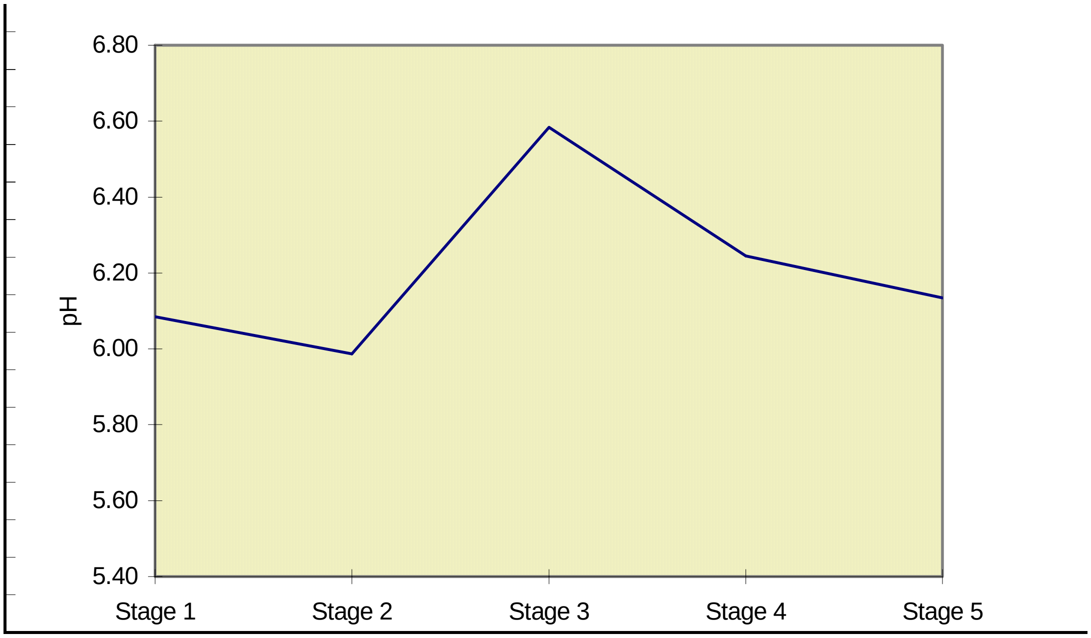
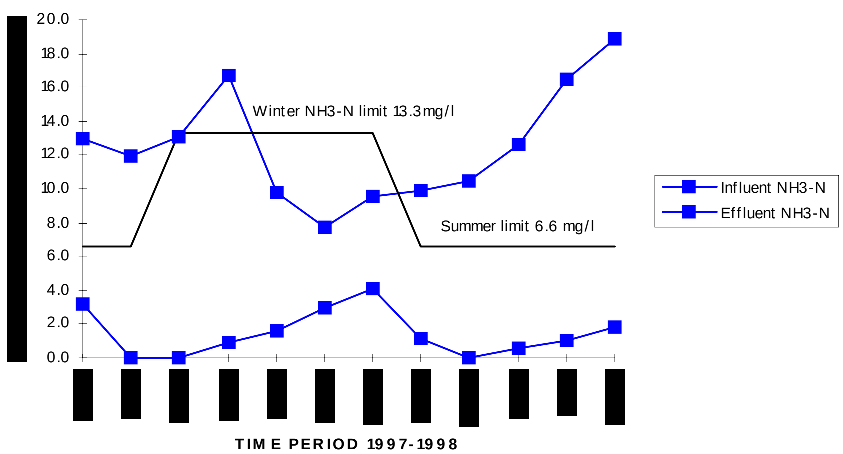


Figure 9D
Morganton, NC
Monthly Performance Data for Removal of NH_3-N



Rocky Mount, NC

An example of a complete HPO-BNR system is Rocky Mount, NC. The plant was originally designed with a conventional HPO system for BOD removal from a combined municipal/textile wastestream. In the early 1990's the first stage of the HPO reactor was converted so that the wastewater is now exposed to an anaerobic environment followed in series by an anoxic compartment. The reactor cover was also removed from an intermediate stage to facilitate CO_2 stripping.

The configuration of the original and converted reactors is given in Figure 10A. **(See Figure 10A "Rocky Mt., NC – Reactor Configuration")**
Monthly performance data from 1996-1997 for removal of NH_3-N and total P is given in Figure 10B. **See Figure 10B "Rocky Mt., NC Monthly Performance Data for Removal of NH3-N and Total P")** Excellent results of <0.5 mg/l NH_3 and total P were observed.

FIGURE 10A
Rocky Mt., NC - Reactor Configuration

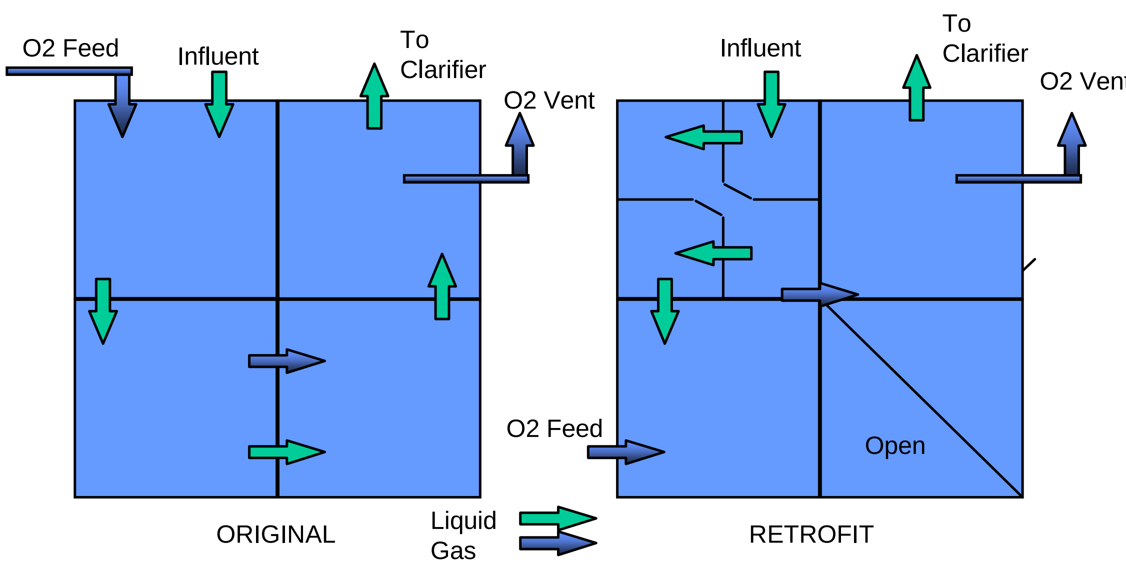
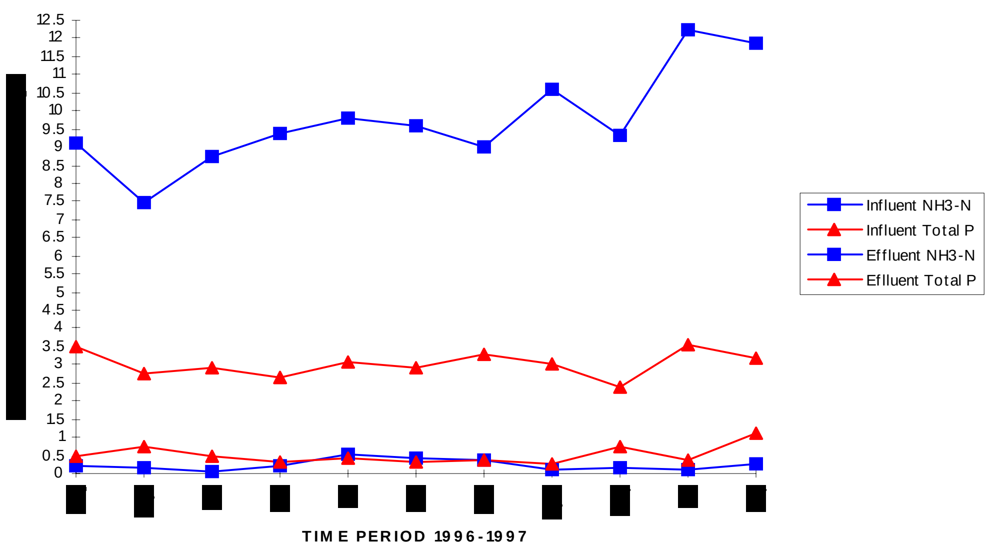


FIGURE 10B
Rocky Mount, NC
Monthly Performance Data for Removal of NH_3-N and Total P



SUMMARY OF HPO SYSTEM IMPROVEMENTS

The capabilities of the conventional HPO process have been expanded and improved with the incorporation of the following developments:

- Anaerobic reactor zone for phosphorus removal and/or biological selector capability.
- Anoxic reactor zones for denitrification (single or dual).
- Open oxic stage for CO_2 stripping and pH elevation.
- Improvements in surface aerator devices available which offer substantially improved transfer efficiency for the UNOX-BNR system.
- Advances in vacuum swing adsorption technology substantially lowering the specific power consumption for generating on-site oxygen.

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