Improving Design of the BNR Process in Wastewater Treatment Plants from an Operations Perspective

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THE FLORIDA STATE UNIVERSITY
COLLEGE OF ENGINEERING

IMPROVING DESIGN OF THE BNR PROCESS IN WASTEWATER TREATMENT PLANTS FROM AN OPERATIONS PERSPECTIVE

By

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A Thesis submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of Master of Science

Degree Awarded:
Spring Semester, 2004
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<table>
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<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alum</td>
<td>Aluminum Sulfate</td>
</tr>
<tr>
<td>BNR</td>
<td>Biological Nutrient Removal</td>
</tr>
<tr>
<td>BPR</td>
<td>Biological Phosphorus Removal</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical Oxygen Demand</td>
</tr>
<tr>
<td>CNC</td>
<td>Charlotte North Carolina</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>gpd</td>
<td>Gallons per Day</td>
</tr>
<tr>
<td>ISS</td>
<td>Inert Suspended Solids</td>
</tr>
<tr>
<td>mgd</td>
<td>Million Gallons per Day</td>
</tr>
<tr>
<td>mg/L</td>
<td>Milligrams per Liter</td>
</tr>
<tr>
<td>MLSS</td>
<td>Mixed Liquor Suspended Solids</td>
</tr>
<tr>
<td>OUR</td>
<td>Oxygen Uptake Rate</td>
</tr>
<tr>
<td>Ortho-P</td>
<td>Orthophosphate</td>
</tr>
<tr>
<td>OTE</td>
<td>Oxygen Transfer Efficiency</td>
</tr>
<tr>
<td>OTR</td>
<td>Oxygen Transfer Rate</td>
</tr>
<tr>
<td>TP</td>
<td>Total Phosphorus</td>
</tr>
<tr>
<td>PAO</td>
<td>Phosphorus Accumulating Organism</td>
</tr>
<tr>
<td>PHB</td>
<td>Poly-β-Hydroxybutyrate</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>RAS</td>
<td>Return Activated Sludge</td>
</tr>
<tr>
<td>SRT</td>
<td>Solids Retention Time</td>
</tr>
<tr>
<td>SOTE</td>
<td>Standard Oxygen Transfer Efficiency</td>
</tr>
<tr>
<td>SOTR</td>
<td>Standard Oxygen Transfer Rate</td>
</tr>
<tr>
<td>TKN</td>
<td>Total Kjeldahl Nitrogen</td>
</tr>
<tr>
<td>TSS</td>
<td>Total Suspended Solids</td>
</tr>
<tr>
<td>UCT</td>
<td>University of Cape Town</td>
</tr>
<tr>
<td>VFA</td>
<td>Volatile Fatty Acid</td>
</tr>
<tr>
<td>WAS</td>
<td>Waste Activated Sludge</td>
</tr>
<tr>
<td>WWTP</td>
<td>Wastewater Treatment Plant</td>
</tr>
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</table>
SOLE NUTRIENT REMOVAL FROM WASTEWATER DISCHARGES HAS BECOME AN INCREASING CHALLENGE, AS REGULATORY AUTHORITIES TIGHTEN DISCHARGE STANDARDS TO AVOID EUTROPHICATION PROBLEMS IN RECEIVING WATERS. ENGINEERS HAVE BECOME AWARE THAT THERE IS A NEED FOR NEW ENGINEERING DESIGN OF STANDARD WASTEWATER TREATMENT PLANTS THAT SHOULD INCLUDE REMOVAL OF NUTRIENTS (NITROGEN AND PHOSPHORUS) IN AN EFFICIENT AND COST EFFECTIVE MANNER. THIS NEED LED TO THE DEVELOPMENT OF BIOLOGICAL NUTRIENT REMOVAL (BNR) PROCESS, WHICH IS A DISTINCTIVE MODIFICATION OF THE BASIC ACTIVATED SLUDGE PROCESS. THE BNR PROCESS IS CONTROLLED IN BIOREACTOR WITH SEPARATE ZONES THAT CREATE DIFFERENT BIOCHEMICAL ENVIRONMENTS, WHICH ALLOW THE SYSTEM TO REMOVE A HIGH DEGREE OF NITROGEN AND PHOSPHORUS FROM THE WASTEWATER. THERE ARE MANY UNCERTAINTIES AND UNCONTROLLABLE FACTORS IN THE BNR PROCESS, THEREFORE ACHIEVING HIGH RELIABILITY DEPENDS HEAVILY ON KNOWLEDGEABLE OPERATORS AND ENGINEERS. OPERATORS AND START-UP ENGINEERS CAN HELP DESIGN ENGINEERS BECOME MORE KNOWLEDGEABLE ABOUT UNIQUEENESS IN DESIGN BY PASSING ON KEY INFORMATION THAT BECOMES AVAILABLE DURING OPERATIONS. THIS INFORMATION WAS COLLECTED AND USED TO IMPROVE DESIGN’S LAYOUT OF BNR BIOREACTOR TO ACCOMMODATE ALL OBSERVED OPERATIONAL DEFICIENCIES.

THE DEFICIENCIES FOUND DURING OPERATIONS WERE RELATED TO START-UP CONDITIONS, CLIMATE, PROCESS RELATED ISSUES AND EQUIPMENT SPACING. START-UP CONDITIONS, CLIMATE AND EQUIPMENT NEED TO BE CONSIDERED MORE CLOSELY DURING DESIGN. ENGINEERS CAN LEARN FROM THE PROCESS RELATED DEFICIENCIES FOUND DURING OPERATIONS TO IMPROVE THE PROCESS DESIGN.
OBJECTIVE

For the standard treatment of municipal and industrial wastewaters, the activated sludge process is the most widely used biological process. The typical activated sludge process consists of an aeration basin, a settling basin, solids recycle from the settling basin to the aeration basin, and sludge wasting. The aeration zone is a basin containing microbial aggregates or flocks of microorganisms termed activated sludge. The activated sludge is kept in suspension due to aeration or mixing. When the treated wastewater and microbial aggregates move to the settling basin, the microorganisms are removed from the wastewater by settling and returned to the aeration basin or wasted. This leads to high concentrations of microorganisms in the system, so the sludge is called activated since it has a higher concentration than if the microbials were not recycled. The clean effluent from the settling basin is discharged to the environment or given further treatment (Rittmann and McCarty, 2001).

Nutrient removal from wastewater discharges is an increasing challenge for water authorities, as regulatory authorities tighten discharge standards to avoid eutrophication problems in receiving water. Modification of the traditional activated sludge process has been developed to focus treatment toward biological system for the control of nitrogen and phosphorus in wastewater effluent. The specialized process, biological nutrient removal (BNR), utilizes baffles or walls for creating zones with different environmental conditions. These encourage the selective growth of certain types of microorganisms that work specifically to remove nitrogen and phosphorus from wastewater (Water Environment Federation, 1996).

The success of the activated sludge process including biological nutrient removal does not mean that it is a perfect process. Achieving reliable treatment for wastewaters presents a great challenge to engineers and operators today. Operators have little control over the flow rate or composition of the influent wastewater. In addition, the ecology of the system can change daily and the success of the operation depends on microorganisms being monitored with unrefined
methods. There are many uncertainties and uncontrollable factors, however the activated sludge process is still considered successful. Achieving high reliability depends on knowledgeable operators and engineers (Rittmann and McCarty, 2001)

The main objective of this research was to improve the overall engineering design of wastewater treatment plant’s biological nutrient removal (WWTP-BNR) by correcting poorly designed elements that are causing start-up and operational problems when facility is built and running. The summary of proposed corrections and changes was based on the following layout: (1) initial interviews of start-up and operational engineers; (2) development and distribution of questionnaires to the WWTP-BNR plant’s operators; (3) analysis of obtained results; (4) development of sequences of changes based on “individual problem-proposed engineering solution” type; and (5) development of manual of changes and suggestions to be used by design engineers.

The starting point for this study included compilation of compendium of information to improve the design for activated sludge and specifically biological nutrient removal (BNR) processes. This collection consisted of specifically how activated sludge and BNR methods and flexibility have been incorporated into wastewater treatment plants. This investigated plug flow operations and different modes of biological nutrient removal including biological nitrogen and phosphorus removal. The information collected was coming from wastewater treatment plant design engineers, but more specifically from start-up engineers and operators so as to get a new perspective on suggestions for wastewater treatment process improvements. The conclusion of this research includes a manual to be used by design engineers to improve wastewater treatment plant BNR designs taking into consideration the design suggestions of operators and start-up engineers. This manual can be used in conjunction with BioWin, CMAS or other BNR simulation tools for design and analysis of specific treatment plant systems to better predict the process behavior. This manual should provide some direction in examining trial and error scenarios in the software as well as providing some physical design improvements.
The purpose of wastewater treatment is to remove pollutants that can harm the aquatic environment if they are discharged into it. Because of the harmful effects of low dissolved oxygen (DO) concentrations on aquatic life, wastewater treatment engineers historically focused on the removal of pollutants that would deplete the DO in receiving waters. (Grady et al., 1999)

As industrialization and population growth continued, another problem was recognized, eutrophication. Eutrophication is the process by which a body of water undergoes an input of excessive nutrients, primarily nitrogen and phosphorus, initiating a sequence of algal growth (bloom) and decay that ultimately depletes oxygen and alters biodiversity. Some algae species may produce toxins that lead to fish lesions and threaten local economy and health. Algal blooms can reduce water quality to the point where it is no longer suitable as a drinking water source, even after treatment (Hecky and Kilham, 1988).

Inputs from both point and non-point sources may elevate nutrient levels in lakes and rivers. Stormwater run-off is typically the most significant contributor in wet weather conditions, and wastewater treatment plants (WWTPs) are often the major contributors in dry weather conditions. The level of impact in the receiving water is not only dependent on pollutant loading, but also the degree of dispersion and dilution available, as well as the characteristics of the specific aquatic ecosystem. Nutrient levels in rivers and streams are fundamentally linked to flow conditions. Especially during periods of low flow, fine sediment, organic matter, and sediment-bound phosphorus accumulate within rivers and streams, increasing nutrient levels. Inputs from WWTPs are diluted less when stream flows are low (Hecky and Kilham, 1988).

Engineers have become concerned with the design of wastewater treatment systems that can remove these pollutants in an efficient and cost effective manner, and much research during the past two decades has focused on processes for doing that. This research has resulted in the
development of numerous nutrient removal processes. The basic activated sludge process is a flexible, reliable process capable of removing soluble organic matter, stabilizing insoluble organic matter, and achieving a high degree of nitrification. The activated sludge process consists of an aeration basin, a settling basin, solids recycle from the settling basin to the aeration basin, and sludge wasting. The addition of denitrification and phosphorus removal to the activated sludge process was necessary to prevent discharges of high nutrient concentrations to receiving waters. This need led to the development of biological nutrient removal (BNR). BNR is a modification of the basic activated sludge process and is distinguished by the division of the bioreactor into alternative biochemical environments. BNR systems are capable of removing a high degree of nitrogen and phosphorus from the wastewater. Supplemental chemical additions may also be utilized, depending on the degree of removal to be achieved (Grady et al., 1999).

A typical wastewater treatment plant consists of different levels of treatment depending on the discharge limits required to ensure protection of public health and the environment. Treatment can include preliminary, primary, advanced primary, secondary, secondary with nutrient removal, tertiary and advanced treatment. Table 1 provides a description of these levels of wastewater treatment.

Table 1 - Levels of Wastewater Treatment

<table>
<thead>
<tr>
<th>Treatment Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary</td>
<td>Removal of wastewater constituents such as rags, sticks, floatables, grit, and grease that may cause maintenance or operational problems with the treatment operations, processes, and ancillary systems.</td>
</tr>
<tr>
<td>Primary</td>
<td>Removal of a portion of the suspended solids and organic matter from the wastewater.</td>
</tr>
</tbody>
</table>
### Table 1 - Continued

<table>
<thead>
<tr>
<th>Treatment Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Primary</td>
<td>Enhanced removal of suspended solids and organic matter from the wastewater. Typically accomplished by chemical addition or filtration.</td>
</tr>
<tr>
<td>Secondary</td>
<td>Removal of biodegradable organic matter (in solution or suspension) and suspended solid. Disinfection is also typical included in the definition of conventional secondary treatment.</td>
</tr>
<tr>
<td>Secondary Treatment with Nutrient Removal</td>
<td>Removal of biodegradable organics, suspended solids, and nutrients (nitrogen, phosphorus, or both nitrogen and phosphorus).</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Removal of residual suspended solids (after secondary treatment), usually by granular medium filtration or microscreens. Disinfection is also typically a part of tertiary treatment. Nutrient removal is often included in this definition.</td>
</tr>
<tr>
<td>Advanced</td>
<td>Removal of dissolved and suspended materials remaining after normal biological treatment when required for various water reuse applications.</td>
</tr>
</tbody>
</table>


In the basic activated sludge process, a flocculent slurry of microorganisms (mixed liquor) is maintained in an aerated bioreactor to remove soluble and particulate organic matter from the influent waste stream. Subsequent quiescent settling in a clarifier is used to recover the biological floc from the process flow stream. Return activated sludge (RAS) is the settled solids that are recycled as concentrated slurry from the clarifier back to the bioreactor. Waste activated sludge (WAS) is the excess solids that are wasted to maintain a designated solids retention time (SRT) to a desired value (Linden et al., 2001; Grady et al., 1999).
The distinguishing feature of a BNR system is the division of the bioreactor to provide alternative biochemical environments. A BNR system may consist of biological phosphorus removal, biological nitrogen removal, or both biological phosphorus and nitrogen removal. In addition, the bioreactor of a BNR system is divided into anaerobic, anoxic, and aerobic zones, with provision for biomass recycle, as illustrated in Figure 1. These three zones are distinguished by the terminal electron acceptor utilized. Oxygen is the electron acceptor in the aerobic zone, while nitrate is used as the electron acceptor in the anoxic zone, and neither oxygen nor nitrate is present in the anaerobic zone. (Grady et al., 1999).

Figure 1. Bioreactor of a BNR system – anaerobic, anoxic, and aerobic zones.

(Linden et al., 2001)

The aerobic zone is a necessary component of all BNR systems and indicates zones which contain dissolved oxygen (DO). The anaerobic zone is necessary to accomplish phosphorus removal, is a zone that has an input of organic substrate, contains no DO, and has no input of nitrate nitrogen. The anoxic zone is necessary for nitrogen removal, has a DO of less than .5mg/L and has an input of nitrate nitrogen. Table 2 summarizes the biochemical
transformations occurring in the various zones of a BNR process. It also presents the functions that these zones provide, as well as which zones are required to remove each nutrient. (Grady et al., 1999; Water Environment Federation 1996).

Table 2. Summary of BNR Process Zones. (Linden et al., 2001)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Biochemical Transformation</th>
<th>Functions</th>
<th>Zone Required for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic</td>
<td>Uptake and storage of VFAs by PAOS</td>
<td>Selection of PAOs</td>
<td>Phosphorus removal</td>
</tr>
<tr>
<td></td>
<td>Fermentation of readily biodegradable organic matter by heterotrophic bacteria</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anoxic</td>
<td>Denitrification</td>
<td>Conversion of nitrate to nitrogen gas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alkalinity production</td>
<td>Selection of denitrifying bacteria</td>
<td>Nitrogen removal</td>
</tr>
<tr>
<td></td>
<td>Nitrification</td>
<td>Conversion of ammonia to nitrite and nitrate</td>
<td>Nitrogen removal</td>
</tr>
<tr>
<td></td>
<td>Metabolism of stored and exogenous substrate by PAOs</td>
<td>Nitrogen removal through gas stripping</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phosphorus uptake</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerobic</td>
<td>Alkalinity consumption</td>
<td>Formation of polyphosphate</td>
<td>Phosphorus removal</td>
</tr>
</tbody>
</table>

In the past decade, a great deal of interest and investigative effort has been directed toward biological systems for the control of phosphorus and nitrogen in wastewater effluent. Basically, the processes developed can be considered as modifications of conventional activated-sludge technology. Processes have been developed for nitrogen removal by biological nitrification and denitrification only, biological phosphorus removal only, and removal of both nutrients in dual or combined systems. Depending on the effluent residual requirements and reliability attainment goals, some chemicals may be to be added to supplement these processes (Water Environment Federation, 1996).

Further study of the mechanisms, microbiology, stoichiometry, and kinetics of BNR systems has led to the development of many system variations. Each variation is typically named after the person who invented the new process or the treatment plant where the process was first
discovered or implemented. The different modes in the BRN process typically include variations in zone order as well as variations in recycle flows. The variations allow different parts of the biological nutrient removal to be improved. Some processes work better to remove phosphorus while others are specifically meant for nitrogen removal only. BNR modes are selected on a site-specific basis and depend on many factors, including influent wastewater characteristics and level of treatment to be achieved. A summary of the advantages and disadvantages of each biological nutrient removal (BNR) process variation is presented in Table 3 (Linden et al., 2001).

<table>
<thead>
<tr>
<th>Process</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLE</td>
<td>Good nitrogen removal</td>
<td>High level of nitrogen removal not generally possible</td>
</tr>
<tr>
<td></td>
<td>Moderate reactor volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alkalinity recovery</td>
<td>Not designed for phosphorus removal</td>
</tr>
<tr>
<td></td>
<td>Good solids settleability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced oxygen requirement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simple control</td>
<td></td>
</tr>
<tr>
<td>Four-Stage Bardenpho</td>
<td>Excellent nitrogen removal</td>
<td>Large reactor volume</td>
</tr>
<tr>
<td></td>
<td>Alkalinity recovery</td>
<td>Not designed for phosphorus removal</td>
</tr>
<tr>
<td></td>
<td>Good solids settleability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced oxygen requirement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simple operation</td>
<td></td>
</tr>
<tr>
<td>A/O</td>
<td>Minimum reactor volume</td>
<td>Phosphorus removal adversely impacted if nitrification occurs</td>
</tr>
<tr>
<td></td>
<td>Good phosphorus removal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good solids settleability</td>
<td>Not designed for nitrogen removal</td>
</tr>
<tr>
<td></td>
<td>Reduced oxygen requirement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simple control</td>
<td></td>
</tr>
<tr>
<td>Phostrip</td>
<td>Good phosphorus removal</td>
<td>Complex operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phosphorus removal adversely impacted if nitrification occurs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost of chemicals to precipitate Phos</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not designed for nitrogen removal</td>
</tr>
<tr>
<td>A2/O</td>
<td>Good nitrogen removal</td>
<td>High level of nitrogen removal not generally possible</td>
</tr>
<tr>
<td></td>
<td>Moderate reactor volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alkalinity recovery</td>
<td>Moderate phosphorus removal</td>
</tr>
<tr>
<td></td>
<td>Good solids settleability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced oxygen requirement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simple control</td>
<td></td>
</tr>
<tr>
<td>VIP</td>
<td>Good nitrogen removal</td>
<td>High level of nitrogen removal not generally possible</td>
</tr>
<tr>
<td></td>
<td>Good phosphorus removal</td>
<td>An additional mixed liquor recycle step is required</td>
</tr>
<tr>
<td></td>
<td>Moderate reactor volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alkalinity recovery</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good solids settleability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced oxygen requirement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High rate process</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simple control</td>
<td></td>
</tr>
<tr>
<td>UCT</td>
<td>Good nitrogen removal</td>
<td>High level of nitrogen removal not generally possible</td>
</tr>
<tr>
<td></td>
<td>Good phosphorus removal</td>
<td>An additional mixed liquor recycle step is required</td>
</tr>
<tr>
<td></td>
<td>Moderate reactor volume</td>
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<tr>
<td></td>
<td>Alkalinity recovery</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good solids settleability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced oxygen requirement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simple control</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Summary of BNR process advantages and disadvantages.
The most prevalent forms of nitrogen in wastewaters that may require treatment are organic, ammonium and nitrate nitrogen. The presence of nitrogen in a wastewater discharge is undesirable for several reasons. As is well known, a free ammonia is toxic to fish and many other aquatic organisms, and an ammonium ion or ammonia is an oxygen-consuming compound which will deplete the dissolved oxygen in receiving water. In all forms, nitrogen can be available as a nutrient to aquatic plants and consequently contribute to eutrophication. Also, nitrate ion is a potential public health hazard in water consumed by infants. In summary, depending upon local circumstances, removal of all forms of nitrogen or just ammonium may be required. (Argaman et al., 1991)

Nitrogen removal processes incorporate aerobic zones for nitrification, anoxic zones for denitrification, and mixed liquor recirculation (MLR) to transfer the nitrate-N generated in the aerobic zone back to the initial anoxic zone. Nitrification is an aerobic process and will occur only in the aerobic zones. Denitrification is the conversion of nitrate-N to nitrogen gas by
heterotrophic bacteria that utilize nitrate-N as their terminal electron acceptor as they oxidize organic matter in the absence of dissolved oxygen. Denitrification occurs in the anoxic zones. (Grady et al., 1999).

Nitrogen can occur in many forms in wastewater and undergo numerous transformations in wastewater treatment. These transformations allow the conversion of ammonia-nitrogen to products that can easily be removed from the wastewater. In nitrification-denitrification, the removal of nitrogen is accomplished in two conversion steps. In the first step, nitrification, the oxygen demand of ammonia, is reduced by converting it to nitrate. However, the nitrogen has merely changed forms and not been removed. In the second step, denitrification, nitrate is converted to a gaseous product for removal (Metcalf and Eddy, 1991).

**Nitrification**

Two bacteria are responsible for nitrification, Nitrosomonas and Nitrobacter. Nitrosomonas oxidizes ammonia to the intermediate product nitrite. Nitrite is converted to nitrate by Nitrobacter. The conversion from ammonia to Nitrite involves a complex series of reactions that control the overall conversion process as evidenced by the lack of nitrite build-up in the system. These equations allow the amount of chemicals required for the processes to be calculated (Metcalf and Eddy, 1991).

Nitrifying bacteria are sensitive organisms and extremely susceptible to a wide variety of inhibitors. A variety of organic and inorganic agents can inhibit the growth and action of organisms. High concentrations of ammonia and nitrous acid can be inhibitory. Typically, inhibition is a concern if significant industrial discharges are present. The effect of pH is also significant. As alkalinity is destroyed, pH will decrease, reducing the nitrification rate. Temperature also exerts an influence on the growth of nitrifying bacteria. The nitrification rate increases with temperature up to a certain point and then decreases. Dissolved oxygen concentrations above 1mg/L are essential for nitrification to occur. If DO levels drop below 2
mg/L, nitrification slows or ceases (Jeyanayagam et al., 2000).

**Denitrification**

Denitrification is the second step in the removal of nitrogen by the nitrification-denitrification process. This is the removal of nitrogen in the form of nitrate by conversion to nitrogen gas, and can be accomplished under anoxic (without oxygen) conditions. Conversion of nitrate-nitrogen to a readily removable form can be accomplished by several genera of bacteria including Achromobacter, Aerobacter, Alcaligenes, Bacillus, Brevibacterium, Flavobacterium, Lactobacillus, Micrococcus, Proteus, Pseudomonas, and Spirillum. These bacteria are heterotrophs capable of dissimilatory nitrate reduction, a two-step process. The first step is the conversion of nitrate to nitrite followed by production of nitric oxide, nitrous oxide and nitrogen gas (Metcalf and Eddy, 1991).

The process of denitrification requires the presence of nitrates, absence of DO, and a source of rapidly biodegradable organic matter (RBOM). If DO is present, the microbes will preferably use the free oxygen. Sources of RBOM include influent wastewater, endogenous decay, and external carbon source (methanol). Significantly higher denitrification rates are achieved when the RBOM source is influent wastewater or methanol (Jeyanayagam et al., 2000).

In denitrifying systems, dissolved oxygen concentration is the critical parameter. The presence of DO will suppress the enzyme system needed for denitrification. Alkalinity is produced during the conversion of nitrate to nitrogen gas resulting in an increase in PH. The optimal PH lies between 7 and 8 with different optimums for different bacterial populations. Temperature affects the removal rate of nitrate and the microbial growth rate. The organisms are sensitive to changes in temperature (Metcalf and Eddy, 1991).
Biological Phosphorus Removal

Phosphorus is an essential macronutrient that spurs the growth of photosynthetic algae and cyanobacteria, leading to accelerated eutrophication of lakes. Wastewater discharges that reach lakes sensitive to eutrophication often require phosphorus removal over and above that normally taking place in primary and secondary treatment (Rittmann and McCarty, 2001). The approach of removing phosphorus from municipal wastewaters to control nuisance aquatic plant growth is entering its third decade. The localized water quality problems can be expected to lead to lower and lower effluent phosphorus limitations. Improving the understanding of the mechanisms behind biological phosphorus removal will lead to broader and more efficient application of this approach. (Argaman et al., 1991)

Phosphorus is found in wastewater in three principle forms: orthophosphate (ortho-P) ions, polyphosphates, and organic phosphorus compounds. During wastewater treatment, much of the polyphosphate and organic phosphate content is converted to ortho-P, and inorganic phosphates are utilized in forming biological floc. Treatment plant removal efficiency must be based on total phosphorus entering the plant in the raw wastewater and total phosphorus discharged in the plant effluent (Grady et al., 1999; Linden et al., 2001).

Biological phosphorus removal can be accomplished introducing the phosphorus accumulating organisms (PAO) in the sludge to influent that contains volatile fatty acids (VFA) in a zone that is free of nitrates and dissolved oxygen. In this zone phosphorus is released from the sludge. In the following zone, the aeration zone, the PAO’s re-accumulate the phosphorus in excess of their true synthesis needs. When nitrification occurs in the aeration basin, nitrates will be present in the return activated sludge (RAS) and must be removed by some form of denitrification before the RAS reaches the anaerobic zone where the nitrates would hinder true anaerobic conditions (Johnson and Barnard, 2002).
Acinetobacter are one of the primary PAO’s responsible for removal of phosphorus. These organisms respond to volatile fatty acids (VFA’s) in the influent wastewater under anaerobic conditions by releasing stored phosphorus. For this reason, the VFA’s are important for the acinetobacter. Biological phosphorus removal requires both anaerobic and aerobic zones. When an anaerobic zone is followed by an aerobic zone, the microorganisms exhibit phosphorus uptake above normal levels. Phosphorus is utilized for cell maintenance, synthesis, and energy transport and also stored for later use by the microorganisms. The sludge containing the excess phosphorus is either wasted or removed and treated in a side stream to release the excess phosphorus, which occurs in an anoxic environment (Metcalf and Eddy, 1991).

**Computer Based Modeling Tools for BNR Design**

Modeling of activated sludge processes has become a common part of the design and operation of wastewater treatment plants. Models today are being used in design, control, teaching and research. The incorporation of computer-based modeling tools into design has greatly improved the ease with which biological process modeling can be implemented (Henze et al., 2000).

Process modeling software, such as BioWin (BioWin32, 2003), GPS-X (GPS-X, 2001), allow engineers and operators to examine what-if scenarios in wastewater treatment plants without making changes to operations for a trial and error purpose that could be detrimental to the performance of the plant (Phillips and Shaw, 2002).

A simulation tool like BioWin can set model stoichiometric and kinetic parameters, schedule operating parameters such as temperature, dissolved oxygen and airflow, simulate biological activity and simulate plant start-up scenarios using the variable volume bioreactor element (Biowin32, 2003).

During the initial development of the process models, it was realized that due to the long solids retention times and low growth rates of the bacteria, actual effluent substrate concentrations between different activated sludge treatment plants did not vary greatly. However, there was a
significant difference in the levels of MLSS and electron acceptor (oxygen or nitrate). So, the focus of the activated sludge model is on the prediction of the amount and change of the solids and electron acceptor. The model is based COD as the measurement for the quantity of organic matter since mass balances can be carried out on it. The organic material is categorized according to a number of characteristics including biodegradability of the material. The biomass is modeled by heterotrophic or autotrophic and the nitrogenous material is categorized by the biodegradable ability and physical state (GPS-X Reference Manual 4.0, 2001).

The simulation of activated sludge systems including carbon oxidation, nitrification and denitrification account for a large number of reactions between a large number of components. To provide realistic predictions, the models represent the important fundamental processes occurring in the system. The models also quantify both the kinetics and the stoichiometry of each process (Henze et al., 2000).

Simulation models such as BioWin are powerful tools which allow environmental professionals to accurately simulate the performance of activated sludge systems. However, there is a high level of expertise required and a large amount of time required to configure and calibrate the models (Bratby et al., 2001). The benefits outweigh the negatives and include the optimization of aeration basin design, examination of the effectiveness of alternate treatment strategies, evaluation of the impacts of future water quality standards, and identification of influences of dynamic process variations on daily effluent quality. The result of using such software includes a design providing high flexibility, innovative biological nutrient removal configurations that are readily adaptable to a variety of alternative treatment configurations, and providing operators with substantial flexibility to meet future changes in effluent requirements (Buhr et al., 2001).
METHODOLOGY

To achieve the objective of this study, initial interviews were conducted with numerous individuals who are involved in the activated sludge and biological nutrient removal (BNR) processes by design or operations. These interviews were with individuals who have worked on start-up of wastewater treatment plants from the operational side as well as individuals who have designed these treatment plants. A search was also conducted for information related to activated sludge and BNR flexible design successes and failures related to treatment plants.

The process was started by interviewing key individuals knowledgeable in the most recent technology relating to BNR and wastewater treatment plant design and operations. These interviews were a beginning so that enough knowledge could be gained to successfully comprise a questionnaire directed to operators and design engineers who are associated with start-ups and operations of wastewater treatment plants. The comments of a colleague, who has been directly involved in the design and start-up of a wastewater treatment plant in Charlotte, North Carolina, were used to refine the questionnaire, and it was distributed by e-mail to a number of other individuals to provide first hand knowledge of their experiences and recommendations for wastewater treatment plant design. These individuals proved to be quite knowledgeable. The results of these interviews and questionnaires were then analyzed and collaborated to form a collection of suggestions for the improvement of design of wastewater treatment plants biological nutrient removal processes. (The questionnaire is attached in Appendix B.) Finally, after analysis of the results, a manual was created to provide easy availability to these design improvements.

Development of Questionnaire

As a beginning, key individuals knowledgeable in the most recent technology relating to BNR and wastewater treatment plant design and operations were interviewed so that enough knowledge could be gained to successfully comprise a questionnaire directed to operators and
design engineers who are associated with start-ups and operations of wastewater treatment plants. The comments of a colleague, who has been directly involved in the design and start-up of a wastewater treatment plant, were used to refine the questionnaire.

The final questionnaire included 12 questions related directly to the BNR process concerns first introduced during the initial interviews. These concerns were associated with low loads during start-up, process deficiencies, lack of volatile fatty acids, geographic locations, physical limitations such as equipment problems and flexible design plants including step feed. One question was dedicated to any additional comments or suggestions the operator or start-up engineer could think of that did not fit under the subtopics of each question.

It was a concern that the questions would be too broad and specific information would not be provided with the responses, however, it was an equal concern that the questions would be too specific and maybe not encompass a particular individual’s area of expertise. The expectation of the responses was to provide information related to specific experiences or problems encountered in the BNR process operations or start-up by the individual surveyed and any solutions found successful, if any, that could be passed on to design engineers to improve future designs and avoid similar difficulties.

**Analysis and Results**

The analysis of the questionnaire responses started with a grouping of the problems reported by the operators and start-up engineers into six categories. The problems were then evaluated in two ways; first the probability of finding a solution was considered, and second the number of treatment plants with a particular problem was also considered. The focus of the engineering solutions evaluation was given to the problems found by more than one treatment plant of the more than 50 treatment plants represented. After evaluating the problems to be the focus of this research and categorizing them into sections, solutions or recommendations for the engineering deficiencies were determined. A sequence of changes was developed based on a “problem – proposed engineering solution” type. The solutions were grouped into six categories including
process improvements, adjustments for low flows, instrumentation and control improvements, climate control improvements, chemical feed improvements and equipment considerations.

**Development of Manual**

The manual was developed by organizing the found problems and recommended engineering solutions in a manner that would be easy for a design engineer to follow and use independently from this thesis. Figures were included in the manual to easily be skimmed into order to find suggestions of interest to an engineer with particular treatment plant characteristics. Detailed engineering recommendations follow the figures for further explanations. The manual can be used in conjunction with modeling software for design and analysis of specific treatment plant systems to better predict the process behavior. The manual should provide some direction in examining trial and error scenarios in the software as well as providing some physical design improvements.
RESULTS

Surveyed Plants Location

The operators and start-up engineers that were a part of this research proved to have key information that became available to them during operations of many wastewater treatment plants. The collected information was gathered from 8 individuals and included knowledge and experience from over 50 wastewater treatment plants in 14 states as shown in Figure 2. These wastewater treatment plants were spread across the United States including all types of climates and geographical difficulties such as extremes in temperature and land availability issues.

Figure 2 – Locations of Researched Wastewater Treatment Plants.
The design capacity for the researched treatment plants ranged from 3 mgd to 30 mgd and included different types of BNR treatment. Most plants included only nitrogen removal but some included both nitrogen and phosphorus removal. These plants that included phosphorus removal were limited to the Southwest, specifically Arizona, Florida and the Chesapeake Bay area. Plants in Arizona use wastewater effluent for reuse such as watering golf courses, which requires phosphorus removal. The Midwest is starting to consider phosphorus removal and one plant in Missouri has already incorporated it. Phosphorus removal will probably take another five to ten years to become more widespread.

Typically the treatment plants surveyed were expansions or upgrades with the exception of the North Carolina plant that was new when the operator currently working started his career. The BNR arrangements varied from typically plug flow to complete mix to designs that included a little of everything allowing the ultimate in flexibility and requiring high levels of operator knowledge and experience. One Plant in North Carolina was considered almost too flexible causing operators to have trouble keeping the processes running smoothly.

**Analysis of Questionnaire**

The analysis of the questionnaire responses started with a grouping of the problems reported by the operators and start-up engineers into six categories which are process, equipment, low flows, instrumentation and control, climate control and chemical feed problems. The problems were then evaluated in two ways; first the probability of finding a solution was considered, and second the number of treatment plants with a particular problem was also considered. The focus of the engineering solutions evaluation was given to the problems found by more than one treatment plant of the more than 50 treatment plants represented. Table 4 was comprised to more clearly show the number of responders complaining about a particular problem and therefore the number of treatment plants that equated to having a particular problem.
Table 4 - Reported Problems

<table>
<thead>
<tr>
<th>Reported Problem</th>
<th>Number of responses experiencing particular problem</th>
<th>Equivalent Treatment Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process Problems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terms become outdated</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Clarifier overflows</td>
<td>4</td>
<td>46</td>
</tr>
<tr>
<td>Flow goes by untreated because flow introduced too late</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Need to bypass clarifiers</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Anaerobic digesters</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Trickling filters</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Equipment problems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foam trapped behind baffles</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>Not enough space around equipment</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>Equipment failure</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td><strong>Low Flow Problems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anoxic zone destroyed</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>Phosphorus release</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Start-up conditions not considered</td>
<td>3</td>
<td>36</td>
</tr>
<tr>
<td><strong>Instrumentation and Control Problems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control schemes not user friendly</td>
<td>5</td>
<td>46</td>
</tr>
<tr>
<td>Difficult to control recycle flows</td>
<td>4</td>
<td>55</td>
</tr>
<tr>
<td>Sampling</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Too much flexibility</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Climate Control Problems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keep DO up in cold weather</td>
<td>3</td>
<td>35</td>
</tr>
<tr>
<td>Nitrify in cold weather</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Scums beaches freeze</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Chemical Related Problems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of VFA’s</td>
<td>4</td>
<td>56</td>
</tr>
<tr>
<td>Spikes in phosphorus</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>Low alkalinity</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Construction reduces plant capabilities</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Hydralic/organic under loading</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Discussion

The conducted interviews and the answered questionnaires focused on operational deficiencies associated with the biological nutrient removal process of wastewater treatment plants. This information can help design engineers become more knowledgeable about uniqueness in design that becomes apparent only during operations. Table 5 through Table 10 show operational deficiencies and recommended solutions. Each table addresses one of six pertinent categories which are process improvements, equipment considerations, adjustments for low flows, instrumentation and control improvements, climate control improvements and chemical feed improvements. Explanation for each item will follow each table.

Table 5 – Process Improvements

<table>
<thead>
<tr>
<th>PROBLEMS</th>
<th>SUGGESTED SOLUTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terms become outdated as the processes are updated.</td>
<td>Use the term Activated Sludge Basins instead of Aeration Basins since the anoxic and anaerobic zones are mixed and the oxic zone is aerated. The system should be called the activated sludge basin since now we have activated sludge basins with anaerobic, anoxic, and oxic zones.</td>
</tr>
<tr>
<td>With step feed systems, the clarifier Sludge blanket may cause the clarifier to overflow.</td>
<td>Step feed: Apply the RAS at the beginning of the flow near the influent flow in step feed so that the clarifiers are not overtaxed since they are the bottleneck of the system. (See Figure 4)</td>
</tr>
<tr>
<td>During plug flow often the flow is introduced too late which allows less hydraulic residence time so flow can go by untreated into the clarifiers and it may cause the plant to violate permits for BOD, COD, nitrogen and phosphorus.</td>
<td>Do not add too much flow at the end of the aeration basins. A plug flow system with 25% of the flow added in four equally spaced apart locations along the basin is acceptable. (See Figure 4)</td>
</tr>
</tbody>
</table>
Table 5 Continued

| Clarifier sludge blanket (which may be 2-3 feet of sludge in the bottom of the clarifier) will rise and overflow the clarifier weir. | The final clarifiers have a limiting load for every Sludge Volume Index (SVI) of the sludge. A sludge with a smaller SVI means the clarifier will have better settling. An SVI of 75 is good, whereas 150 would mean there could be problems. The limiting load must not be exceeded or the sludge blanket will cause the clarifier to overflow. 25lb/day of TSS per square foot of clarifier surface area is standard. (See Figure 4) |

Terms become outdated as the processes are updated: The biological nutrient removal process is continually being improved. As the process is changing the vocabulary become outdated and terms need to be updated. It is important to pay attention to how the process is evolving and change the vocabulary to keep current. The term activated sludge basins should be used instead of aeration basins since the anoxic and anaerobic zones are mixed and the oxic zone is aerated. The system should be called the activated sludge basin since now we have activated sludge basins with anaerobic, anoxic, and oxic zones.

With step feed systems, the clarifier Sludge blanket may cause the clarifier to overflow: Sometimes biological nutrient removal basins are designed for step feed influent. The influent flow is fed in many places, but the return activated sludge (RAS) should be introduced to the basin in one place, in the front, as shown in Figure 4, so there is a longer sludge retention time because you hold more sludge in the process. As you feed further down the basin the mixed liquor concentration in the front is higher. The reason for this is to not overflow the clarifier. The clarifier is the limiting factor. It is limited by the sludge loading rate. If the sludge loading rate is exceeded, the clarifier starts overflowing. So, when the feed is lower down, the solids load on the clarifier is lower, so you can carry a higher sludge inventory without taxing the clarifiers. The RAS can be introduced to the basin in front next to the influent flow. It is helpful if the RAS flow is installed so that it is either at a lower elevation than the influent flow or
entering perpendicular to the influent flow. This will allow the two flow streams to mix at their introductions into the basins and will alleviate concerns with short circuiting.

**During plug flow often the flow is introduced too late which allows less hydraulic residence time so flow can go by untreated into the clarifiers and it may cause the plant to violate permits for BOD, COD, nitrogen and phosphorus:** Plug flow is a standard design in New York City because of the lack of land available. Typically the plants there are step feed since more flow can get through without washing out solids. Step feed is always a good option when the land available is limited. There is the same sludge age but there are lower mixed liquor suspended solids (MLSS) in the last zone. Here the RAS goes into the first pass and the flow is introduced in four places. The first pass gets the RAS and only 25% of the flow. The mixed liquor concentration will thus be high. In the second pass another 25% of the flow is introduced and the ML concentration is further reduced until you get to the last pass at which time you have the full flow going in. The zone configuration showing 4 inputs of 25% of the flow can be seen in Figure 4. Thus only the last pass is at the concentration that you would have in the whole basin if you had introduced all the flow in the first pass. The higher concentrations in the previous passes amount to carrying a higher solids load while the clarifiers still sees the same flow and concentration and thus the same load. If the RAS concentration is 7000 mg/L then the MLSS in the first zone may be 5000 mg/L. The MLSS in the second may be 4000 mg/L and the third 3000 mg/L and in the fourth only 2,500 mg/L. If all the flow were to go to the first pass the whole basin would be at 2,500 mg/L. A concern with step feed is adding too much flow at the end of the Aeration Basins. This allows less hydraulic residence time which could cause flow to go by untreated into the clarifiers and the plant may also be violating permits for BOD, COD, nitrogen and phosphorus.

**Clarifier sludge blanket (which may be 2-3 feet of sludge in the bottom of the clarifier) will rise and overflow the clarifier weir:** The final clarifiers have a limiting load for every Sludge Volume Index (SVI) of the sludge. A smaller SVI (ml/g) means the clarifier will have better settling. A good SVI may be approximately 75, whereas an SVI of 150 and above may mean
there will be problems. If this limiting load is exceeded or if the sludge pumps are not pulling sludge out fast enough, or if the sludge is a fluffy, poor settling sludge then the sludge blanket, which may be two to three feet of sludge in the bottom of clarifier, will not settle to the bottom of clarifier and the sludge will start to come out over clarifier weir so the sludge blanket will rise and overflow. The clarifier is thus the bottleneck in the plant. The location of the clarifiers in the BNR process can be seen in Figure 4. If we reduce the MLSS to them they can handle more flow. To alleviate stress on the clarifiers, 25lb/day of TSS per square foot of clarifier surface area is suggested.

<table>
<thead>
<tr>
<th>Table 6 – Equipment Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeration Basin Foam trapped behind baffles</td>
</tr>
<tr>
<td>Often there is not enough space allotted around equipment for safe operator access or maintenance.</td>
</tr>
<tr>
<td>When equipment fails or requires maintenance the rental equipment can be extremely expensive.</td>
</tr>
</tbody>
</table>

**Aeration basin foam trapped behind baffles:** Sometimes baffle walls are required to help prevent short circuiting in a basin, as shown in Figure 4. Baffle walls need to be ½ inch under the water surface so the foam produced by the tank can flow over top of the baffles and not get trapped behind the baffles. If baffles are just below the water surface elevation the flow goes around the baffles but scum does not get trapped behind the baffles. Scum pits can be placed at
the end of the basins where scum and foam can flow over a weir into the pit to be pumped to the digesters. When a plant has deeper tanks, it is easy to get short circuiting over the top of the baffles. A solution for this is to install chimneys in the basins so the flow will discharge into a chimney which takes the flow right down to bottom of tank. If there are more baffles the flow will run over the next baffle and then another chimney can be installed to take the flow down to the bottom of the tank again.

**Often there is not enough space allotted around equipment for safe operator access or maintenance:** When laying out equipment locations the design engineer should consider what occurs during routine and corrective maintenance procedures for each piece of equipment. Allow ample space to remove motors or internal parts. For example, pump actuators are usually at least a foot larger than the actual pump. The location of this actuator needs to be taken into consideration. The actuator should be placed on the side of the pump where there is access space provided for an operator or maintenance person. Three feet is the minimum space required for operator access.

**When equipment fails or requires maintenance the rental equipment can be extremely expensive or not available:** It is important to provide back-up systems for all critical components including necessary piping and appurtenances. Often, when a piece of equipment fails or requires maintenance rental equipment is required, if a back-up was not provided, to keep the process running. This can be more expensive than if a stand-by piece of equipment had been installed from the beginning, or it could be impossible. For example, the competitive bid for a vertical recirculating pump may be $35,000 requiring six weeks for manufacturing and shipment. This pump could not be produced as a rental in less than six weeks. The plant would require an immediate replacement in the event a pump required maintenance and could not wait six weeks. It is suggested that stand-by pumps and blowers be installed with necessary piping from the beginning of the project to always have a back-up available for these critical components. RAS pumps are a perfect example of critical equipment that always should have backup pumps in place as shown in Figure 3. Some equipment, at the client’s request, may require a back-up be placed in storage in case of equipment failure.
## Table 7 – Adjustments for Low Flows

<table>
<thead>
<tr>
<th>Anoxic zone destroyed during low flow periods.</th>
<th>Turning off the internal recycle during the low flow periods of start-up, and using RAS instead to provide oxygen and nitrates and nitrites, works to allow a truly anoxic zone without having too much free oxygen. This must be worked out in advance with the engineers and operators. (See Figure 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteria are around too long during low flow periods causing the release of phosphorus instead of take-up.</td>
<td>BNR zones need to have the ability to reduce the detention time for lower flows than design. Often the zones are designed for ultimate flows that may not be achieved for years. The detention time for the anaerobic zone should typically be 30 – 45 minutes for design flow. During start-up this can be corrected by taking the zones offline proportional to the flow. (See Figure 3)</td>
</tr>
<tr>
<td>Start-up conditions are often not considered during design which causes numerous flow related problems.</td>
<td>The designer is trying to create a particular environment to treat wastewater. This same environment must be created during start-up based on the lower loading.</td>
</tr>
</tbody>
</table>

**Anoxic zone destroyed during low flow periods:** If a plant is designed with flexibility as a consideration it is easier to make necessary adjustments during start-up to correct for the low flows or low loads. When there are low loadings at facilities during start-up, internal recycle (oxic recycle) flow rates can be cut back to start-up the denitrification process and then the return activated sludge flow rate is relied on to provide recycle flow so the anoxic zones are not destroyed. When there is low loading during start-up it is difficult to sustain the anoxic zones all hours of the day because during low loading periods the aerobic zones and oxic zones get highly concentrated with dissolved oxygen. In other words, the loadings are so low the nitrification process happens so rapidly in the space available that the dissolved oxygen values end up in the 3, 4 or 5 mg/l range and if the needed internal recycle flow rate is maintained to
supply the oxygen back to the anoxic zone then there is so much free oxygen the anoxic zone cannot keep going. Sometimes the internal recycle is limited based on the turndown capabilities of the internal recycle pumps. Occasionally, these pumps need to be turned off and just the return activated sludge (RAS) from the final clarifiers flow rate provides enough nitrites and nitrates back to the process to maintain the anoxic zone. Internal recycle, which was set at about two times the influent flow rate, returns flow from the end of the oxic zone back to the anoxic zone. In low load situations, high dissolved oxygen (DO) in the oxic zone is created because there is no demand. When the internal recycle is brought back to the anoxic zone, if there is not enough load to take up the free oxygen then free oxygen will destroy the anoxic zone. Then there will be no denitrification taking place. Turning off the internal recycle during the low flow periods, and shown in Figure 3, and using RAS instead to provide oxygen and nitrates and nitrites allows there to be a truly anoxic zone. If this is the method chosen to get through the start-up low load periods, it must be worked out with the operators.

Another plant that was designed for an 8 mgd treatment train only was running at 2 mgd for a time at start-up. The full connections to the plant were not made until three to four months after start-up. The internal recycle pumps could not be used because the anoxic zone was lost for 16 hours a day due to the low loadings. So, the return activated sludge was relied on to return enough nitrates and nitrites to maintain the anoxic zone. The return activated sludge flow rate was a little higher, but it worked and is a good way to get around problems related to low loads.

**Bacteria is around too long during low flow periods causing the release of phosphorus instead of take-up:** Biological nutrient removal zones need to have the ability to reduce the detention time for lower flows such as during start-up conditions as shown in Figure 3. Often the zones detention times are designed for ultimate flows that may not be achieved for years. The detention time for the anaerobic zone should be 30 - 45 minutes for design flow, but should not be any longer than 1 to 1½ hours. The detention times or the number of basins needs to be reduced for lower start-up flows. Zones or treatment trains need to be taken out of service proportional to the flow at start-up and remain offline until flows and loads approach the design conditions. If the bacteria are allowed to remain in the system too long secondary phosphorus
release can occur and because there is no energy since the volatile fatty acids are depleted, subsequent aerobic uptake of the released phosphorus may not be possible. Elevated effluent phosphorus levels could result.

**Start-up conditions are often not considered during design which causes numerous flow related problems:** An important concept from a design standpoint is to not only design for the plant conditions in the future, but it is also important to operations to design for start-up conditions as well. During design phase, it is important for the biological nutrient removal processes to consider start-up conditions. Consideration must be given to how each zone will be sustained all the time during the low load start-up conditions, which may dictate the size of the basins. The most important concept to consider is that the designer is trying to create a particular environment to treat the wastewater. The same environment must be created during start-up based on the loading and the equipment used, which can be big hurdles. This all must be balanced with the budget.

### Table 8 – Instrumentation and Control Improvements

<table>
<thead>
<tr>
<th>Control schemes are often not user friendly or set up correctly.</th>
<th>Discuss the automatic and local control schemes with the operations and maintenance staff prior to finalizing the specifications.</th>
</tr>
</thead>
<tbody>
<tr>
<td>It is difficult to control the recycle flows when the influent flow varies.</td>
<td>Automate the recycle pumping. Allow one control mode to flow pace based on a percentage of the process influent flow. RAS should be approximately 50-70% of the influent flow whereas the mixed liquor recycle back to the anoxic zone should be 2 to 4 times the influent flow. (See Figure 3)</td>
</tr>
</tbody>
</table>

**Control schemes are often not user friendly or set up correctly:** Operators and maintenance staff will be the ones controlling the treatment plant and therefore should have input into how the plant will operate. Instrumentation and control schemes for equipment, valves, flows and
processes should be discussed with the operators of the plant so they are familiar with the processes and have agreed to the conditions. These control schemes should be logical and user friendly and should be well thought out. During start-up, enough time should be budgeted for the operational specialist to get the plant checked out and allow the clients personnel to have control of the process.

**It is difficult to control the recycle flows when the influent flow varies:** Influent flow to wastewater treatment plants vary from quite low at start-up before all the plant connections have been made to ultimate capacity which may not be reached for years. For example, a plant may be designed for an ultimate capacity of 10mgd, but the average capacity is expected to be 6mgd and the start-up capacity is only at 1.5mgd. Recycle flows for the biological nutrient removal process are set based on a percentage of the influent flows. If this influent flow is variable the operators have a difficult time keeping up with the required recycle flows. These recycle flows therefore need to be automated so the recycle pumping is controlled depending on the influent flows as shown in Figure 3. Allow one control mode to flow pace based on a percentage of the process influent flow. RAS should be approximately 50-70% of the influent flow whereas the mixed liquor recycle back to the anoxic zone should be 2 to 4 times the influent flow. These exact percentages are often determined based on elaborate computer programs taking many variables into account.

**Table 9 – Climate Control Improvements**

| It is difficult to keep DO levels up in warm weather. | As temperature increases the saturation concentration of oxygen decreases so there is less DO in warm water. Cold water sat. concentration is about 11mg/l whereas hot water it may be 6 mg/l. It may require increased cascade reaeration after disinfection to increase DO levels before discharge. A standard DO level required for operation is 2 mg/l. A computer program such as CMAS is required to determine the air required to achieve the necessary DO. |

29
Table 9 - Continued

| It is difficult to nitrify in cold weather | The growth of nitrifying bacteria is cut in half with every drop of 10 deg C. These nitrifiers are not growing fast enough to stay in the system. Cold weather may require doubling the solids retention times or doubling the size of the tanks for every drop of 10 deg C from the design temp to fully nitrify. |

**It is difficult to keep dissolved oxygen (DO) levels up in warm weather:** As temperature increases the saturation concentration of oxygen decreases so it is much harder to dissolve oxygen in warm wastewater so there is less dissolved oxygen (DO) in warm water. Cold water saturation concentration is about 11mg/l whereas hot water it may be 6 mg/l. This is why trout only live in the cold mountains streams since they require a high level of DO. To counteract the low DO, it may require increased blower capacity for aeration or increased cascade reaeration after disinfection to increase DO levels before discharge. A standard DO level required for operation is 2 mg/l. If wastewater influent characteristics include higher biological oxygen demand (BOD), then more air will be required relative to the BOD to increase the DO levels. A computer program such as CMAS is required to incorporate all variables and determine the air required to achieve the necessary DO.

**It is difficult to nitrify in cold weather:** The growth of nitrifying bacteria is cut in half with every drop of 10 deg Celsius. These nitrifiers are not growing fast enough to stay in the system. Cold weather may require doubling the solids retention times or doubling the size of the tanks for every drop of 10 deg C from the design temp to fully nitrify. In climates with wide temperature ranges, flexible design plants will be necessary to allow longer retention times and more basins to come online to counteract the difficulties associated with colder temperatures and slower growing nitrifiers.
Table 10 – Chemical Feed Improvements

| Lack of VFA’s | Waste product from soft drink manufacturers can be used as a sugary waste to take out phosphate if there is a lack of VFA’s. A 6 mgd plant could require as much as 660,000 gallons of acetic acid to keep the VFA’s at the required level of 20 mg/l. (See Figure 3) |
| Spikes in the phosphorus in the system. | It may be that there are high levels of phosphorus in the filtrate from the anaerobic digesters which is brought back to the plant. A 6 mgd plant may require 300 gallons per day of Alum added to the primary clarifiers to precipitate out the phosphorus. |
| Low alkalinity | A typical 6 mgd plant may require 200 parts of alkalinity to oxidize the existing ammonia. To keep the PH at 6-9 leaving the plant another 100 parts of alkalinity are required. A typical plant may only have 140 parts of alkalinity coming into it, so a 30% lime slurry can be used to increase the alkalinity to the required levels for discharge (7.14 mg CaCo3 are required per mg of ammonia). |
| Too much load for a plant when part of the plant is offline for construction. | A 2.5 mgd plant may only have 1.5 mgd capabilities during construction. Place a 10,000 gallon tank near the influent pump station and trickle in magnesium hydroxide to the influent to reduce the loading to match the plant capabilities. |

**Lack of VFA’s:** Some organisms can take up volatile fatty acids (VFA’s) in the anaerobic zone and store them as intermediate products. The organisms need oxygen but they cannot get it so they use all the phosphate they have accumulated as an energy source because phosphate bonds are energy bonds. The polyphosphate accumulated serves as battery for taking up the VFA’s. When the organisms get to the aerobic zone, they have the food they stored and they can use oxygen and burn up the food and now take up all phosphate around them. The cycle starts with the use of phosphate to take up food in anaerobic zone, then in aerobic zone the organisms use
the food to take up the phosphorus again, but they have gained so they can take up more phosphorus than they released. When the organisms take up the VFA’s they break down as poly-phosphorus bonds and they give off phosphate, so the phosphate concentration is high in the anaerobic zone, up to three to four times the input, which is positive because it means the take-up is occurring in anaerobic zone. VFA’s are essential to this process. Many plants have enough VFA’s in the influent so producing more is not a concern. It is often naturally there, especially when waste is pumped over a long period. In a force main you have a slime layer in the pipe and that produces VFA’s. When there are a lack of VFA’s available, there are some options to produce VFA’s.

Fermenters produce more VFA’s. The normal procedure is to digest sludge. There are bacteria that break the sludge down to acetic acid, which is the lowest oxidized form. Acetic acid is what phosphorus accumulating organisms (PAO’s) need. The key to a phosphorus removal plant is the availability of VFA’s and placing them in the right location where no nitrate and no oxygen is found. Otherwise the other bacteria can use the VFA’s. All bacteria would use VFA’s since they are very readily degradable. If there is a supply of oxygen or nitrates then the VFA’s will be wiped out in no time. If nitrogen and oxygen are excluded from the basin then only PAO’s can get it. Nothing else can break it down further because it is an anaerobic end product, so it cannot be broken down further. So, bacteria that use nitrate as electron acceptor cannot use it, and those that use oxygen cannot use it. Biological phosphorus organisms which store phosphate can use phosphate as an energy source to pick up the VFA’s. The basins need to be protected from oxygen and nitrate and needs to be supplied with enough VFA’s so that these PAO’s can grow. When you have the right combination, they grow and start taking phosphorus out of wastewater.

The overall goal is to get a basin somewhere in the system where these PAO’s can be subjected to VFA’s, in absence of oxygen and nitrates, to give them the opportunity to take up the phosphorus in the aeration zone. It is important to make sure the nitrates are gone so there are no nitrates in the waste activated sludge (WAS) coming back in the tank. If nitrification occurs, the configuration of the plant is not important. The basin can be anywhere in the system as long as
no nitrate and oxygen are coming into it. However, it will need to be followed with aeration to take up phosphate again.

It is important in a BNR plant to not bring phosphorus back to the plant. If the phosphorus is removed and then put on anaerobic conditions, the phosphorus will be released again, and more VFA’s are needed to take out the phosphate again. Acetic acid can be bought and put into a plant and it works great to remove phosphate, but it is expensive. A sugary waste can be used instead, as shown in Figure 3, which breaks down fast into acetic acid. Very low effluent phosphorus values can be achieved using additions of sugary waste. An inexpensive means to obtaining this is from the waste product from soft drink manufacturers.

Problems that can occur are if the VFA’s in the influent are not as high as were expected. The plant can be augmented with acetic acid, but it is costly to buy. A sugary waste can be used and put in the fermenter and it will immediately break down to VFA’s. A small portion of molasses can be fed into the fermenter, which helps to produce VFA’s since it is a sugary waste. A problem with putting sugar in the anaerobic zone is that it may encourage the growth of other bacteria that is not wanted, but if the sugary waste is put in the fermenter and brought down to acetic acid, then it is the right media for the biological phosphorus organisms. A plant with insufficient VFA’s can be supplemented with acetic acid. One particular 6 mgd plant discussed during this research required 660,000 gallons of acetic acid to keep the VFA’s at required level of 15 to 20 mg/l. The exact amount of acetic acid required to increase the level of the VFA’s will include many variables and needs to be determined by a computer program such as CMAS or BioWin.

**Spikes in the phosphorus:** A problem encountered related to the BNR process is spikes in the phosphorus in the system related to a high level of phosphorus in the filtrate from the anaerobic digesters. This filtrate was the liquid from the belt filter presses, which was brought back to the beginning of the plant to be treated. As the filtrate went through the plant the spikes in phosphorus were found. This 6mgd plant required 300 gallons per day of Alum added to the primary clarifiers to precipitate out the phosphorus. A portion of this, as required, could also be added to the final clarifiers just in case the phosphorus was not all removed. It is important to
avoid spikes in the process by equalizing flow from every process. The filtrate return to the beginning of the plant needs to be metered back evenly to avoid spiking the plant.

**Low Alkalinity:** One BNR plant in North Carolina was having trouble with low alkalinity. This plant required 210 parts of alkalinity to oxidize the existing ammonia. The effluent of the plant requires 60 to 100 parts of alkalinity to maintain a PH of 6 to 9 leaving the plant. The sum of 210 parts plus 100 parts equals 310 required parts of alkalinity. The plant only had 140 parts coming into the plant. The alkalinity was increased by adding lime slurry to the process consisting of 30% lime (7.14 mg CaCO3 are required per mg of ammonia). This increases the alkalinity to the appropriate levels.

**Construction:** A problem associated with the plant expansion process is related to the time during construction when half the plant may need to be offline while construction is taking place. At this time you may have, for example, a 2.5mgd plant with half the basins offline, so essentially only 1.5 mgd plant capabilities while 2.5 mgd of flow and load are still coming through. The plant can handle the larger flows but not the larger loads associated with more flow. Magnesium hydroxide can take off some of the loading by removing BOD and some solids. A 10,000 gallon tank of magnesium hydroxide is sufficient for a 2.5 mgd plant and can be placed near the influent pump station and trickled into the influent to remove some of the loading and allow the plant to handle the larger flows through less plant to get through construction. The exact amount of magnesium hydroxide to be trickled will have to be experimented with and samples will be required to test that enough is being added based on the results of the loading samples from the influent during construction.

**Implementation**

The following two figures are available to show, in a typical activated sludge process with biological nutrient removal, where and how the improvements resulting from this research can be implemented. Figure 3 shows the typical activated sludge process with BNR and Figure 4 includes suggestions related to a plug flow BNR scheme.
Turn off internal recycle during low flow periods when flow is 25% less than design and rely on RAS to provide oxygen, nitrates and nitrites to limit the free oxygen and allow a truly anoxic zone.

Add sugary waste to fermenter then to anaerobic zone to keep VFA’s at a minimum of 20 mg/l to promote phosphorus removal. (6 mgd plant = 35 gal/day of 30% acetic acid)

Reduce detention time to 30 minutes for lower flows than design.

Automate RAS to be proportioned at 50-70% of the influent flow.

Provide back up equipment for critical components such as pumps for RAS.

Figure 3 – Activated Sludge Process
Baffles constructed ½ inch below water surface elevation so foam can flow over the baffles.

Apply RAS at beginning for step feed so clarifiers are not overtaxed. Apply RAS immediately adjacent to or perpendicular to the influent flow to facilitate mixing.

Do not add too much flow at the end of the aeration basins since this will allow less hydraulic residence time so flow could go by untreated and violate permits. 25% of flow added at four equally spaced apart locations is acceptable.

A smaller SVI means the clarifier will have better settling. An SVI of 75 is good whereas 150 means there could be problems. If this is too high, the sludge blanket can rise and overflow. (25 lb/day of TSS per square foot of clarifier surface area is acceptable).

Figure 4 – Step Feed Activated Sludge Process
Quantification of Changes

Dissolved Oxygen Example

The following example shows the basic equations as well as the computer program simulation that can be used to determine air flow requirements for an aeration basin in the BNR process.

When dissolved oxygen (DO) drops below the desired value of 2 mg/l in a wastewater treatment plant BNR system, the aeration to the basin should be increased as necessary. The following equations will show the basic relationships between dissolved oxygen and air flow requirements for aeration basins.

The oxygen required for treatment varies with BOD loading and can be calculated by

\[ DO = 1.25 \times \text{BOD} \]

where

DO = oxygen requirements, lb/hr; and
BOD = BOD removal, lb/hr.

Oxygen requirement can be converted to an airflow rate for diffused air systems by the following equation:

\[ A = 95.2 \times \frac{DO}{TE} \]

where

A = Required air flow in cu ft/ min,
DO = Oxygen requirement, lb/hr, and
TE = Oxygen transfer efficiency in the waste, percent.

The following example uses a computer modeling program called BioWin to compare air flow with temperature and more accurately predict the aeration requirements for an aeration basin for a wastewater treatment plant with particular influent characteristics. This is just an example based on very particular treatment plant characteristics and the output numbers cannot be used as a rule, but only to illustrate the relationship of required airflow to temperature.
Air Requirements Example:

A wastewater treatment plant utilizing BNR consists of a primary clarifier, three bioreactors and a final clarifier and has influent characteristics as shown in Table 11.

Table 11 – Influent Characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>4.65 mgd</td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>544 mg/L</td>
<td></td>
</tr>
<tr>
<td>TKN</td>
<td>33 mg/L</td>
<td></td>
</tr>
<tr>
<td>Total P</td>
<td>5.4 mg/L</td>
<td></td>
</tr>
<tr>
<td>ISS</td>
<td>28.92 mg/L</td>
<td></td>
</tr>
<tr>
<td>BOD</td>
<td>257.27 mg</td>
<td></td>
</tr>
</tbody>
</table>

Source: BioWin input

For this example the temperature is altered in BioWin between 5 degrees Celsius, 20 degrees Celsius and 35 degrees Celsius with all other factors remaining the same. These temperatures represent the probable extremes in temperature depending on the region where the treatment plant is located or the time of year the aeration system is implemented. Tables 12, 13 and 14 depict the airflow requirements produced as results from the BioWin program. Appendix D shows the actual program output pages.

Table 12 – Airflow Requirements at 5 Degrees Celsius

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUR (Tot.)</td>
<td>28.9</td>
<td>mgO/L/hr</td>
</tr>
<tr>
<td>OUR (Carbonaceous)</td>
<td>18.7</td>
<td>mgO/L/hr</td>
</tr>
<tr>
<td>OUR (Nitrogenous)</td>
<td>10.2</td>
<td>mgO/L/hr</td>
</tr>
</tbody>
</table>
Table 12 Continued

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denitrification rate</td>
<td>0.1399</td>
<td>mgN/L/hr</td>
</tr>
<tr>
<td>SOTE (%)</td>
<td>32.73</td>
<td>%</td>
</tr>
<tr>
<td>SOTR</td>
<td>583.34</td>
<td>lb/hr</td>
</tr>
<tr>
<td>OTE (%)</td>
<td>13.11</td>
<td>%</td>
</tr>
<tr>
<td>OTR</td>
<td>233.71</td>
<td>lb/hr</td>
</tr>
<tr>
<td>Air supply rate</td>
<td>1703.28</td>
<td>ft³/min</td>
</tr>
<tr>
<td>Air flow rate / diffuser</td>
<td>0.84</td>
<td>ft³/min</td>
</tr>
<tr>
<td># of diffusers</td>
<td>2034</td>
<td>Diffusers</td>
</tr>
<tr>
<td>Flow</td>
<td>9.99</td>
<td>Mgd</td>
</tr>
</tbody>
</table>

Source: BioWin output

Table 13 – Airflow Requirements at 20 Degrees Celsius

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUR (Tot.)</td>
<td>45.9</td>
<td>mgO/L/hr</td>
</tr>
<tr>
<td>OUR (Carbonaceous)</td>
<td>23</td>
<td>mgO/L/hr</td>
</tr>
<tr>
<td>OUR (Nitrogenous)</td>
<td>23</td>
<td>mgO/L/hr</td>
</tr>
<tr>
<td>Denitrification rate</td>
<td>0.1785</td>
<td>mgN/L/hr</td>
</tr>
<tr>
<td>SOTE (%)</td>
<td>29.26</td>
<td>%</td>
</tr>
<tr>
<td>SOTR</td>
<td>971.14</td>
<td>lb/hr</td>
</tr>
<tr>
<td>OTE (%)</td>
<td>11.06</td>
<td>%</td>
</tr>
<tr>
<td>OTR</td>
<td>367.1</td>
<td>lb/hr</td>
</tr>
<tr>
<td>Air supply rate</td>
<td>3171.25</td>
<td>ft³/min</td>
</tr>
<tr>
<td>Air flow rate / diffuser</td>
<td>1.56</td>
<td>ft³/min</td>
</tr>
<tr>
<td># of diffusers</td>
<td>2034</td>
<td>Diffusers</td>
</tr>
<tr>
<td>Flow</td>
<td>9.99</td>
<td>Mgd</td>
</tr>
</tbody>
</table>

Source: BioWin output

Table 14 – Airflow Requirements at 35 Degrees Celcius

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUR (Tot.)</td>
<td>57.8</td>
<td>mgO/L/hr</td>
</tr>
<tr>
<td>OUR (Carbonaceous)</td>
<td>29.8</td>
<td>mgO/L/hr</td>
</tr>
</tbody>
</table>
As the temperature increases from 5 °C to 20 °C to 35 °C the total oxygen requirements increase from 28.9 mgO/L/hr to 45.9 mgO/L/hr to 57.8 mgO/L/hr. This shows that the oxygen requirements increase as the temperature increases to account for the lower dissolved oxygen levels in the warmer water. This can be seen clearly in Figure 5.
The other important output number to notice from Tables 12, 13 and 14 include the air supply rate and the air flow rate per diffuser. It can be seen in Figure 6 and Figure 7 that the air supply rate and the air flow rate per diffuser also increase with temperature. The air supply rate is an important value and it is often needed to determine the air supply requirements for the blowers to provide the air to the aeration system for the basins. In the aeration system, the actual number of diffusers stays the same in the calculations, which causes the air flow rate per diffuser to increase. The number of diffusers is more related to the volume of the basin as there is a maximum number of diffusers that will appropriately fit in an aeration system. The airflow rate per diffuser is necessary to provide an appropriate aeration system with necessary diffusers to meet the required airflow for the system.

Figure 6 – Air Supply Rate vs. Temperature
Figure 7 – Air Flow Requirements per Diffuser vs. Temperature

The results of this example are consistent with the recommendations suggested in this research to increase aeration as water temperature increases because DO levels drop in warmer weather. This example using BioWin clearly shows that the total oxygen requirements increase with temperature as well as the total air supply required and the air requirements per diffuser for the aeration system.

**General Parameters and Examples**

The following paragraphs include basic equations and examples that can be used by hand or in conjunction with a computer modeling program to be used as design parameters for improving the design of wastewater treatment plants BNR systems.
F/M Ratios
Activated sludge processes are designed to operate at food to microorganism (F/M) ratios in the range of .2 to .5. F/M ratios can be calculated as
\[ F/M = \frac{(BOD \times Q)}{(MLSS \times V)} \]
where:
- F/M = Food to microorganism ratio, lb BOD / lb MLSS;
- BOD = BOD of aeration basin influent wastewater, mg/l;
- Q = Aeration basin influent wastewater flow, mgd;
- MLSS = Mixed liquor suspended solids, mg/l; and
- V = Volume of aeration basin, mil gal.

Sludge Volume Index (SVI)
Sludge has an independent sludge volume index associated with it which determines the settling characteristics of the sludge. This SVI can be calculated with the following equation:
\[ SVI = \frac{(settled \ sludge \ volume \ (ml/l) \times 1,000)}{MLSS \ (mg/l)} \]
An SVI of 100 or lower indicates sludge having good settling characteristics.

Clarifier Parameters
The following clarifier parameters should be used as a basis for clarifier design.
- Total suspended solids (TSS) = 25 lb/day/sqft
- Average surface overflow rate = 700 gpd/sq ft based on the surface area of the clarifier.
- The maximum surface overflow rate should be limited to 1,400 gpd/sq ft.

Alkalinity
The following is an example for computing the amount of lime to be added to supplement the alkalinity in a wastewater treatment plant. Occasionally a treatment plant can have low alkalinity and require a lime slurry feed to increase the alkalinity to meet permits. A PH of between 6 and 9 is required for plant effluent to meet permit limits. Typically, 7.14 mg of CaCO3 is required per mg of ammonia nitrified.
Example: A typical 6 mgd wastewater treatment plant has 25-30 parts ammonia and 140 parts alkalinity in the plant influent.

30 parts ammonia x 7.14mg of CaCO₃ = 214 parts of alkalinity

This plant will require 214 parts of alkalinity to oxidize the existing ammonia in the plant influent. Alkalinity is required in the amount of 60-100 parts to achieve a PH of 6-9 in the treatment plant effluent to meet permits.

100 parts alkalinity + 214 parts alkalinity = 314 parts of alkalinity

This shows that a total of 314 parts of alkalinity are required to oxidize existing ammonia and keep effluent alkalinity at the appropriate levels. The plant influent only has 140 parts of alkalinity and therefore it must be increased from 140 parts to 314 parts.

314 parts alkalinity – 140 parts alkalinity = 174 parts alkalinity

Therefore, 174 parts of CaCO₃ are required in 30% lime slurry to keep alkalinity at the appropriate levels to maintain required effluent limits for PH.

Recycle Flows

The following recycle flow rates are recommended to be automated into the control system for the treatment plant so the recycle rates will automatically change with the variable influent flow rate.

Return activated sludge (RAS) = .5Q to .7Q = .5 x Influent flow to .7 x Influent flow.

Mixed liquor recycle (ML) = 2Q to 4Q = 200% of influent flow to 400% of influent flow.

VFA’s

Often wastewater treatment plants require addition of acetic acid or a sugary waste to supplement the volatile fatty acid source. The following example shows how the amount of acetic acid to be added to the BNR process can be calculated.

Example: A typical 6mgd wastewater treatment plant needs to keep the VFA’s at 20mg/l in the system.

6mgd x 20mg/l x 8.34 lb/gal = 1000.8 lb/day acetic acid
The acetic acid required is calculated to be 1000.8 lb/day. This can be added in a slurry consisting of a percent of acetic acid depending on where the acetic acid is purchased. Often acetic acid is found in a 30% slurry.

$$1000.8 \text{ lb/day} \times \frac{30\% \text{ acetic acid}}{8.84 \text{ lb/gal}} = 33.9 \text{ gal per day}$$

Using a 30% slurry of acetic acid chemical feed, approximately 34 gal per day of slurry is required to keep the VFA’s at the level of 20mg/l.
CONCLUSIONS

Based on the evaluation of the obtained responses and analysis of the typical design of the biological nutrient removal process for wastewater treatment plants, a number of design improvements were found and are as follows:

• Apply the RAS in the front of the BNR basins near the influent flow in step feed. Clarifiers can become overtaxed when RAS is applied too late not allowing proper sludge retention times and causing large sludge blankets to form.

• Aeration basin step feed should be planned so there are 4 inputs of 25% of the flow equally spaced along the basin. Too much flow added near the end of the basin allows less hydraulic residence time which could leave flow untreated.

• Plan on 25lb/day of TSS per square foot of clarifier surface area. The limiting load of the clarifier, based on the SVI, must not be exceeded or the sludge blanket will cause the clarifier to overflow.

• Baffles need to be constructed ½ inch under the water surface elevation so foam can flow over the baffles. Typically when baffles are designed above the water surface elevation, foam can get trapped behind the baffles and become an operational nuisance.

• When laying out equipment locations consider what occurs during routine and corrective maintenance procedures and operator access. Allow ample space to remove motors and to access controls. Often accessibility is not considered properly creating maintenance problems and safety issues.

• Provide back up equipment for critical components with necessary piping in place. Without back-up equipment, when a piece fails or requires maintenance rental equipment
is required and often more expensive than had a backup been installed from the beginning and is sometimes unavailable.

- Internal recycle pumps should be designed to be turned off during low load start-up. RAS alone can be used instead to provide oxygen and nitrates and nitrites to maintain anoxic zone. During low flow periods, often the anoxic zone can be destroyed due to an abundance of free oxygen.

- BNR zones should be designed in treatment trains and flexibility allowed so treatment trains can be offline during start-up as required. Detention times for anaerobic zones should be 30-45 minutes for design flow and no longer than 1 to 1½ hours. Often the zones are designed for ultimate flows that may not be achieved for years therefore the bacteria is around too long during low flow periods and secondary phosphorus release can occur and permits can be violated.

- Discuss the automatic and local control schemes with the operations and maintenance staff prior to finalizing the specifications. This will alleviate the typical problems often encountered when instrumentation and controls are not designed to be user friendly.

- Recycle flows should be automated and flow paced based on the process influent flows. RAS should be approximately 50-70% of the influent flow whereas the mixed liquor recycle back to the anoxic zone should be 2 to 4 times the influent flow. Without automation operators have a hard time keeping up with the required recycle flows.

- Oversize aeration systems to keep DO levels at 2 mg/l. Simulation software can be used to incorporate all variables and determine the air required to achieve the necessary DO at the warmest temperature probable. Standard aeration systems are unable to keep DO levels up during warm weather due to the decrease in saturation concentration of oxygen with increases in temperature.
• BNR should be set up in treatment trains so trains can be offline until they are needed to help nitrify in cold weather. The retention times or tank sizes need to be doubled with every drop in 10 degrees Celsius below average design temperature. Without flexibility for consideration of lower temperatures full nitrification cannot be achieved.

• A plant with insufficient VFA’s can be supplemented with acetic acid, which is expensive or, alternatively, a waste product from soft drink manufacturer can be used as a sugary waste. The optimum level of VFA’s is approximately 20 mg/l. If VFA’s are not available there will be no phosphorus removal.

• Chemical feed lines of Alum with valves for flow control need to be routed to the primary and final clarifiers with amounts to be determined by simulation software or operations staff. Without Alum, spikes in phosphorus can occur in the system which can be due to many reasons including high levels of phosphorus in the filtrate from the anaerobic digesters.

• A lime silo with 30% lime slurry should be provided on site and routed into the primary clarifiers (7.14 mg CaCO3 are required per mg of ammonia). Alkalinity can be low due to high levels of ammonia and may need to be supplemented to ensure proper operations and to meet permits.

• During expansion construction when portions of the plant are offline, place a 10,000 gallon tank of magnesium hydroxide near the influent pump station to be trickled in to the influent (exact amounts to be determined by a simulation tool) to reduce the loading to match the lower plant capabilities. High loads can continue through the plant not getting properly treated due to limited plant capabilities during construction.

The design manual created for this research is intended for design engineers and includes suggested design improvements gathered in a useful form. This manual can be used in conjunction with BioWin, CMAS or other software used for BNR design to create a more thorough understanding of a particular treatment plant system and better predict the process
behavior. This manual is also providing some direction in examining trial and error scenarios in the software as well as providing some physical design improvements.

**Future Research**

Recommended future research would include a cost evaluation related to the design suggestions proposed by the operators and start-up engineers for this research. This cost evaluation could better determine the cost to performance ratio and therefore predict the potential for treatment plants to actually implement the suggestions included in this research. Future research could also include testing these methods in a treatment plant and taking samples of the wastewater treatment plant effluent to determine more exact values to use as future design standards.
APPENDIX A – Interview Notes

Appendix A includes hand notes taken from two initial interviews which began the data collection process. The first interview was with Person A who has over 40 years of experience as a professional engineer and has done process design for more than 100 nutrient removal plants around the world for domestic and industrial effluents.

The second interview was with Person B who has more than 25 years of experience as a professional engineer in facilities operation and maintenance, operator training, and treatment plant startup. His project experience includes work for both privately owned and municipally owned facilities. The range of projects includes all types of water, wastewater, and biosolids operations.
Notes from interview with person A for Thesis

BioWin
Design Issues  BNR  Flexible designs:
  Modes
  Step feed, plug flow, complete mix

Step feed – RAs up front – hold more sludge
Clarifier overflow

NYCity – get more flow w/o washing out solids

B phosphorous removal – volatile fatty acids essential
Step feed – portion in anaerobic zone – same plant smaller footprint

Fermenter – produce more fatty acids

Trickling filters – get more through same plant

Acetic acid to formic acid
PAO’s – phosphorus accumulating organisms

Basin – VFA’s absence N and O to take up phosphorus
Anaerobic zone – no N and O
Follow with aeration

Pre-anoxic zone – RAS

Buy acetic acid – sugary waste

Nitrate stop fermentation
Acid fermenter – augment with sugary waste – molasses – produce more VFA’s

Baffles cause foam trapped

Tank 20’ deep – use chimney

Mixing energies - 5-7 watts/m^3 in keep solids in suspension

Plastic media to aeration tank to allow nitrifying organisms to grow on them and be retained in the basin to reduce size of basin.
6-7 mm dia cylinder beads
sponge media – heavy
hang ropes – doesn’t work.
Notes from interview with Person B for Thesis

Start-ups – low loads

Full new facility – UCT process – 10mgd bypass – PC’s to give different food load

Physical layout of plant makes things impossible or costly

Low load issues cut back on recycle needed – destroy anoxic zones – high DO

Promoting sampling program

Consider what will start-up conditions be – important *

If orthoP above .5 mg/l then phosphorus release in sludge blanket
Avoid high sludge blanket
Spiral clarifier – speed of sludge collection
Plow collection gets high sludge blanket
Redesign plows to be taller if must be used 12-16” tall
Add drive to increase speed 7-10 ft/min

Create environment for start-up and flexibility

VFA’s – BPR step – VFA/ P ratio 5/1 – 4/1 – 3/1 ok
Appendix B includes the questionnaire that was delivered by e-mail to plant operators and start-up engineers for the purpose of determining treatment plant operational deficiencies. The questionnaire includes 12 questions divided into 5 categories including VFA’s, climate, low flows, equipment considerations and process issues. One question was included for any additional comments responders wanted to include that were not covered in any of the categories addressed.
Questionnaire

1. What suggestions do you have for a wastewater treatment plant designer to make operations and start-up go more smoothly?

2. What are some advantages/disadvantages of new wastewater treatment plants versus retrofits? Do you have an example of a process or concept that was implemented to get around a problem associated with a retrofit?

3. What are some typical start-up problems? Any problems related to low loading? What did you do to get around these issues? Do you have recommendations for designers to keep in mind to help limit these problems?

4. What are some issues relating to flexible design plants? What are problems or successes you have experienced?

5. How can different geographic locations impact treatment plant designs or processes?

6. Explain some of the importance to testing and taking samples. Do you have any examples?

7. How can some of the equipment used in wastewater treatment plants cause problems or be solutions? In other words, what equipment does not work and what does? (Example: spiral clarifier blades vs. plow)

8. What impact do VFA’s have on the processes or the start-up?

9. What advantages or disadvantages are there associated with step feed biological nutrient removal basins?

10. What experience have you had with which zone arrangements for biological nutrient removal and what seems to work the best and why?

11. What challenges arise due to physical limitations of design? What physical aspects of design can improve a process? (Example: the benefits of baffles)

12. Please include any additional comments or specific experiences you have had.
APPENDIX C – Questionnaire Responses

Appendix C includes the questionnaire responses from six individuals two of who were plant operators and four who were start-up engineers. Three of these responses were direct e-mail responses to the questionnaire. Two of these responses came in the form of phone conversations and one of these responses came in the form of a questionnaire alternative which was a list of items to be considered by designers.
Questionnaire Response 1 – Start-up Engineer

This engineer has worked on many plants across the country specifically in Florida, Kansas and Missouri.

1. What suggestions do you have for a wastewater treatment plant designer to make operations and start-up go more smoothly? Constant two-way communication; initially with the utility management, including the utility line staff. The development & implementation of a Utility Start-up & Commissioning team to work along side the Design team ensures continual ‘buy-in’ and understanding of the utilities treatment process goals and the various restrictions placed on the designer. Facilitating the constant ‘educational’ process, the designer can utilize the SU&C team to be internal advocates of the design and provide continual internal-based support of the designer & engineering firm.

2. What are some advantages/disadvantages of new wastewater treatment plants versus retrofits? The advantages of a ‘greenfield’ facility vs. a retrofit are you have limited your ‘problems’ to only those in which your design ‘creates’. Working around an existing facility, the designer must first identify the current and generally ‘hidden’ process limits, identify a means to limit or mitigate those restrictions and balance the variety of design issues related to hydraulic flow patterns and/or site density limitations. An example of a ‘hidden’ process limits may include and leaking isolation valve, ineffective up-stream or downstream process equipment not considered part of the scope of service, seasonal operational practices, lack of operator knowledge base, operator ‘improvements’ not recorded on the facility as-built’s or maintenance equipment ‘improvements’. Do you have an example of a process or concept that was implemented to get around a problem associated with a retrofit?

3. What are some typical start-up problems? SU issues are generally limited to the lack of functional acceptance testing [FAT] of the mechanical, electrical and instrumentation input/output control & monitoring devices. The ‘marriage’ of these three systems to work in conjunction, as a system, is NEVER person’s job. The project SU&C Manager should be assigned the tasks of developing & implementing the FAT schedule. The project SU&C Manager working with the SU&C team comprised of a core group & supplemented personnel, including but not limited to vendors, specialized field sampling & lab support, specialized design engineer support, specialized maintenance electrical/instrumentation & control personnel with troubleshooting skills, during the course of the construction project based on the SU schedule. Any problems related to low loading? Performing SU&C work in Florida during the mid-80’s, dealing with hydraulic/organic under-loading was a constant operational issue. The operating staff developed sloppy habits and ‘created’ operational problems out of thin air. First example the facility is both hydraulic/organic under-loaded and the dissolved oxygen concentration attains saturation for the ambient temperature of the water. The operators would perceive a ‘high’ D.O. as a problem because of excessive facility electrical consumption; operator-based solution – turn the blower flowrate down or cycle ‘on/off’. Except the reduction in blower flowrate or cycling the blower ‘on/off’ allowed for under-mixing of the aeration basins creating a low D.O. environment within the floc & portions of the basin, below the diffusers or in the corners of a rectangular shape basin, and filamentous bacteria would become dominate creating solids settling issues in the final clarieier and/or inhibit nitrification due to the lack of D.O..
second example occurred when the facility hydraulic & organic loading capacity was double from 12 to 24 mgd even though the current ADF was 8.0 mgd with max day hitting 14 mgd. The new equipment was placed into service receiving raw influent flow, the old facility was not taken out of service. and the new facility O&M manual provided instructions to operate at a target MLSS of 1,800 to 2,000 mg/L. The operators promptly stop wasting sludge in an unsuccessful attempt to ‘drive’ the facility MLSS up to the 18.00 to 2,000 mg/L concentration. By the time I was involved, the facility was experiencing anaerobic digester problems because the operators had stopped wasting for the preceding 90+ days. The digesters were inactive, the primary clarifier effluent BOD was greater than the influent BOD and the final clarifiers solids collectors were in ‘over-torque’ condition due to excessive depth of blankets. What did you do to get around these issues? The key for the 2cd facility was to explain to the operating staff the need to waste sludge on a daily basis & explain the misunderstandings generated by the initial engineers training sessions. We took three of the six clarifiers ‘off-line’ effectively wasting approximately 50% of the solids and targeted the removal from service of other equipment, to reduce the hydraulic capacity & assistance in the long term preventive maintenance program. The staff was introduced to wasting based on SRT an ignoring a target MLSS concentration. The facility was back into compliance, 5 [BOD]-5 [TSS]-2 [TN]-1[TP] within five days. Do you have recommendations for designers to keep in mind to help limit these problems? Design around operating ‘trains’ in round units, 2 – 5 – 8 MGD; allow for flow splitter boxes prior to & after oxic trains to allow for additional/less primary or final clarifiers. VFD controls on RAS, internal recycle and aeration systems allow for effective turn-down capabilities.

4. What are some issues relating to flexible design plants? What are problems or successes you have experienced? Flexible facility designs are fun to create and difficult to teach to the ‘average’ operating staff. The Mc Dowell facility is an example of ‘too much’ process flexibility. The simpler the design, reducing daily decisions by the staff, only improves their ability to be successful.

Flexible designs should focus on additional flushing valveing/piping for pumps, drain lines from tanks, cross-connection valveing/piping for RAS, scum, WAS primary sludge pumping systems. Cross-connections within anaerobic digesters are great; you should try to limit ‘one-way/only way flows’ allowing the staff to ‘pipe around’ a system or component as an example a GBT maybe helpful, ie. during anaerobic digester start-up or if the unit is ‘down’ for corrective maintenance.

5. How can different geographic locations impact treatment plant designs or processes? I have performed start-up, commissioning & troubleshooting for numerous BNR facilities throughout the States including Florida [8], North Carolina [2], Minnesota [2], Michigan [1], South Carolina [1], Arizona [2] and California [2]. The processes are similar; the level of operator understanding is diverse, from poor to dismal. Training of the facility staff should be an on-going concern & be performed by the design engineer @ every design & construction milestone.

6. Explain some of the importance to testing and taking samples. Do you have any examples? My biggest complain is with designers who complain about ‘bad lab data from the client’ but then design using the same ‘bad data –because this is al we have’. If the clients data is suspect – at all- then set-up a 30 day, 24 hour discrete/composite sampler[s] & have both the client and a
commercial lab perform analysis on split samples. The analysis will provide & indicator as to the ‘actual’ quality of the clients lab data and provide ‘actual’ data to form a basis of design. If weather is a factor, then sample during the various seasons to ‘bracket’ the actual raw influent quality.

7. How can some of the equipment used in wastewater treatment plants cause problems or be solutions? In other words, what equipment does not work and what does?
8. What impact do VFA’s have on the processes or the start-up? VFA’s are simply not a issue in FL; long detention time gravity collection times w/consistent high temperatures. No VFA’s =’s reduced TP removal. If the facility requires VFA’s, an off-line fermenter works great but requires a thinking operating staff. If the staff is operationally challenged, then install an acetic acid chemical feed system.

9. What advantages or disadvantages are there associated with step feed biological nutrient removal basins? I’m not familiar with using step-feed BNR. Personally, I’m not big on step feed; give me a plug flow, complete mix system any day. They tend to be easier to operate & more forgiving to ‘operational oop’s’. You have to questions the design goals –lowest cost –vs. consistent operability & permit limit attainment.

10. What experience have you had with which zone arrangements for biological nutrient removal seem to work the best and why?

11. What challenges arise due to physical limitations of design? What physical aspects of design can improve a process? (Example: the benefits of baffles)

12. Please include any additional comments or specific experiences you have had.

- Unless you allow for the removal of the scum from the oxic basin surface and thereby reducing a headache @ the final clarifier. We did this at several FL facilities by providing a 4 foot flow over weir gate. The weir gate was installed based on the ‘wind rose’ of the site; if the average daily wind blew from the NW, then the gate was installed on the opposite or SE wall [where the scum was already piling up. The staff would lower the weir slightly & hose or ‘draw the scum off the surface using minimal flow & diverted directly to the WAS lines for discharge into the digester/solids handling facilities.
- Yes, yes yes! Flow pace is the only way to allow for effective operational control.
- After primary clarifiers is then the staff is operating ‘one facility’. With a common RAS, you can waste from one clarifier & essential waste from the entire facility. A common RAS means the staff only has to perform one set of process control tests per day. Once again the flexibility issues arises; to send the RAS to a common flow control box or divert each final clarifier to a specific train is a nice feature.
**Response to Questionnaire 2 – Start-up Engineer**

This engineer has worked on many treatment plants across the country from Florida to Minnesota.

1. What suggestions do you have for a wastewater treatment plant designer to make operations and start-up go more smoothly? Plan, plan and more planning. Far too often startup and commissioning is an afterthought.

2. What are some advantages/disadvantages of new wastewater treatment plants versus retrofits? Do you have an example of a process or concept that was implemented to get around a problem associated with a retrofit?

3. What are some typical start-up problems? Any problems related to low loading? What did you do to get around these issues? Do you have recommendations for designers to keep in mind to help limit these problems? Low loading of new plants is frequently a problem. Generally they can be worked around but clients usually fail to understand that cost efficiency may be some years down the road. I have never seen anyone design a plant with the flexibility of the one I am currently working on but even it has problems, especially when it comes to solids handling. One example is the gravity thickener/fermentor. In order to ferment the sludge needs to be in the fermentor for 5 days or so with a 5 foot blanket. The thickened sludge pump was sized for 10 mgd plant capacity. We are at only 20% of this. Therefore the solids are in longer in order to get the required concentration and the pump needs only run a short period of time. This leads to viscosity problems with the sludge, making it very difficult to pull out of the thickener and push to the holding tank 300 feet away.

4. What are some issues relating to flexible design plants? What are problems or successes you have experienced?

5. How can different geographic locations impact treatment plant designs or processes?

I have worked in plants from Florida to Minnesota. Here are a couple of examples.

The wastewater temperature is MN is a lot lower requiring larger aeration tanks to do the same work smaller ones do in FL.

Scum beaches require infrared heating in MN, not so in Florida.

6. Explain some of the importance to testing and taking samples. Do you have any examples??

Testing throughout the treatment plant is extremely important.

With out testing the waste stream concentration you can not accurately set the waste rate to keep the activated sludge process stable.
Running the standard test on anaerobic digesters allows you to see problems that are developing so action can be taken to avert a sour digester. The most important test are the volatile acids and alkalinity, closely followed by temperature.

7. How can some of the equipment used in wastewater treatment plants cause problems or be solutions? In other words, what equipment does not work and what does? (Example: spiral clarifier blades vs. plow)

8. What impact do VFA’s have on the processes or the start-up? Sufficient VFA’s are required in bio P plants. To few VFA’s and the bio-P process will fail.

9. What advantages or disadvantages are there associated with step feed biological nutrient removal basins? The primary advantage seems to be solids loading on the final clarifiers. In step feed the solids loading will be significantly reduced. If sufficient VFA’s are available both remove P very well.

10. What experience have you had with which zone arrangements for biological nutrient removal seem to work the best and why? Sufficient VFA’s are required period. Lacking sufficient VFA’s one would need to produce them ahead of introducing the return stream.

11. What challenges arise due to physical limitations of design? What physical aspects of design can improve a process? (Example: the benefits of baffles) The McKinney weir in final basins on the outer wall to direct bottom currents back to the center of the clarifier. Low solids in the effluent at moderate loading rates can be obtained.

Lack of sufficient scum removal on final clarifiers. I am a firm believer in full radius skimming with ducking skimmers.

The vortex grit removal is much better than any of its predecessors, especially if the grit can be withdrawn without the help of pumps.

Solids storage, frequently undersized to over estimating the WAS concentration.

Having a defoamer in anaerobic digester gas lines. Stops gas lines from becoming clogged with foam.

12. Please include any additional comments or specific experiences you have had.
Response to Questionnaire 3 – Start-up Engineer
This engineer has worked on start-up of numerous plants across the country including Tennessee and North and South Carolina.

1. What suggestions do you have for a wastewater treatment plant designer to make operations and start-up go more smoothly? Bring in someone with operational experience from the beginning. Some process designs and equipment configurations are either difficult to control or beyond the capabilities of the clients personnel.

2. What are some advantages/disadvantages of new wastewater treatment plants versus retrofits? Do you have an example of a process or concept that was implemented to get around a problem associated with a retrofit? New is definitely better. In Franklin Tenn., a retrofit, the construction sequence made it very hard to keep the existing plant in compliance. It involved 4 separate start-ups and shut downs of the new and existing facilities. Obviously no one with any operational experience looked at the sequence. It could have been done with 2 start-ups and shutdowns.

3. What are some typical start-up problems? Any problems related to low loading? What did you do to get around these issues? Do you have recommendations for designers to keep in mind to help limit these problems? The most common problem is trying to start-up plants before they are completely checked out, and ready to start. Often the instrumentation has not been checked out and the plant can start, if you really know what you are doing. We can start them, and operate them because we have started many many plants. Unfortunately the client’s personnel have not and as soon as the operations specialist leaves (because not enough time was budgeted) the client’s personnel lose control of the process and we have to go back. Of course time was not budgeted to do this, so we lose money unnecessarily.

4. What are some issues relating to flexible design plants? What are problems or successes you have experienced? Often because a piece of equipment is expensive only one is put in. Nothing runs forever and when that piece fails or has to have maintenance we scurry around bringing in rental equipment or trying to get around the problem. This usually ends up costing more than installing the equipment originally.

5. How can different geographic locations impact treatment plant designs or processes? Manly temperature. It is real hard to nitrify in Maine in the winter, and hard to keep D.O.’s up in the heat of the South or Southwest.

6. Explain some of the importance to testing and taking samples. Do you have any examples?? During start-up we develop a culture of specific bacteria. There are many signs to watch for during the process. You have to have good sampling to insure the process is heading the right way.

7. How can some of the equipment used in wastewater treatment plants cause problems or be solutions? In other words, what equipment does not work and what does? (Example: spiral clarifier blades vs. plow) Per ferial feed clarifiers do not work well. Screens must have small spacing 1/8” is good. Centrifugal (trash pumps) do not work well for RAS pumping. Grinder
pumps are good. Progressive cavity pumps are very limited when pumping high solids (over 5%). Vortex grit removal is usually so oversized that grit settles out in the influent channels, so when a rain event occur all the channel grit rushes into the unit and plugs them solid. Climber screens stink. They need odor control. Open dumpsters stink. Odor control systems are expensive to operate and are often shut down shortly after start-up. I could go on and on but I have to go to an interview in Hickory.

8. What impact do VFA’s have on the processes or the start-up? Without them BNR will not develop.

9. What advantages or disadvantages are there associated with step feed biological nutrient removal basins? Only one as far as I am concerned. They can handle high flows, (I&I).

10. What experience have you had with which zone arrangements for biological nutrient removal seem to work the best and why? Limited. They need to have the ability to reduce the D.T. for lower flows than design. Often the zones are designed for the ultimate flow, which will not be achieved for years.

11. What challenges arise due to physical limitations of design? What physical aspects of design can improve a process? (Example: the benefits of baffles) Flow control, ability to take out portions of a process at low flows, back up systems, instrumentation that makes sense and can be maintained.

12. Please include any additional comments or specific experiences you have had.
Response to Questionnaire by phone 4 – Notes – Plant Operator
This plant operator has 22 years of experience as an operator with most of his experience consisting of managing operations at a wastewater treatment plant in North Carolina.

New regulations need to remove N and P
Plant oversized to begin with 1980 – design 3 mgd only had 200,000 gallons
Activated sludge didn’t work right – had to leave basins online

Flexibility – bypass clarifiers – at times need less basin than you have.
More flow or loading than we can handle during construction from 3 to 6 mgd
Magnesium hydroxide
½ the plant is taken offline 1995

increase trickling filter rate to ehlp
hydraulically not oversized
firm capacity = one largest pump out of service – state allows that.

Start up on BNR after 6 mgd plant expansion
Series of basins – recycle – ana – anoxic – RAS – WAS
Alkalinity too low – add lime - ph discharge 6-9
140 parts of alkalinity in and 310 parts needed going out.

Low VFA’s – supplement with carbon source - $400,000 per year

Modified UCT process – 3 stage
Recycle rates – not stable – spike when filtrate comes back – phosphorus
Alum
From digester liquid goes to head of plant and solids to solids handling and dewatering
Avoid spiking system with phosphorus.
Equalize flow from every process – EQ basins are good. – flatline flow

Strulite – in anaerobic digestion process in pumps and on BFP rollers– chisel it out
Chemical – polygone – not hazardous helps – try ferric – not work

Equipement start –up issues

Advice on design – keep owner involved in all areas and operators involved too
Response to Questionnaire by phone 5 – Notes – Plant Operator
This operator has worked on many treatment plants specifically in the Southeast.

Hard to nitrify in cold weather because nitrification increases as temperature increases. Need nitrifying bacteria in the system longer - allow more time for bacteria to grow and not get washed
bacteria growths is cut in half with every 10 degree celcius temperature drop.
warm nitrifying bacteria does not grow fast enough so it gets washed out of the system.

Difficult to keep DO’s up in warm temperatures.
temperatures increase sat decreases - less DO in warm water.
Cold water sat. conc 11mg/l -
hot water 6 mg/l.
Trout are in cold mountain streams because they need high DO concentrations to survive.
reaeration or aeration
Not adversely impact the aquatic life - meet discharge regulations.

Nitrification - temperature sensitive.
nitrification rate - degree change in ww temp
SRT double.
In winter the ww Temp. is very low requiring very long SRT's.
In the heat it is much harder to dissolve oxygen in ww
more blower capacity - larger tanks.
point where impossible - enough D.O. - maintain long enough to support the type of aerobes
never seen them get this warm , but the hotter it is the harder it is to maintain D.O.
why trout only live in cold mountain streams - require a high D.O.
The solubility of O2 goes down when temp. goes up.
**Response to Questionnaire Alternative 6 – Start-up Engineer**

This start-up engineer has worked on over 20 treatment plants all across the country.

| Designated the location of control panels and electrical disconnects - too many times the boxes are in a location that does not allow the operator to see the changes being made from the controls. A good example is locating the pump AFD in sight of the flow meter reading. |
| Locate samplers close to power and control connections. Remember that samples have to be flow paced and are not always battery powered. |
| Locate control valves in places that allow safe operator access. |
| Located electrical valve actuators that allow operator access. Many times the valves are located near the ceiling and the controls are on the actuator. In these cases a remote open-stop-close selector switch needs to be located at an operator accessible area. |
| Place phone near the control panel to allow the operator to view control readings while talking to others. |
| Located hose bibs in places that do not require excessive amounts of hoes to be laid out on the ground or along walkways. |
| Discuss the automatic and local control schemes with the operations and maintenance staff. |
| When laying out equipment locations consider what occurs during routine and corrective maintenance procedures. Allow ample space to remove motors and internal parts. |
| Locate seal water strainer blowdown valves away from the equipment so the blowdown does spray onto the equipment or motors |
| Automate the RAS, Anoxic Recycle, and Anaerobic Recycle pumping. |
| Use the term Activated Sludge Basins instead of Aeration Basins |
APPENDIX D – BioWin Output

Appendix D includes printed screens from the output produced by the BioWin program used to simulate the changes in airflow requirements related to temperature change. Typical wastewater treatment plant influent characteristics were given to this example so the output would be likely seen in a full-scale wastewater treatment plant. The output screens produced for this appendix include input temperatures of 5 degrees Celsius, 20 degrees Celsius and 35 degrees Celsius as shown.
BioWin output for Temperature of 5 degrees Celsius
Biowin Output for Temperature of 20 degrees Celsius
BioWin output for Temperature of 35 degrees Celsius
Appendix E includes the manual created for this research as a method to deliver the recommendations herein to design engineers to use to improve future wastewater treatment plant BNR designs. This manual can be taken independently from this thesis to use as a design guide in conjunction with BioWin or other simulation tool or separately for independent design suggestions.
Purpose: To improve the overall engineering design of the biological nutrient removal process for wastewater treatment plants by correcting inadequately designed elements that are causing start-up and operational problems when a facility is built and running.

This manual can be used in conjunction with Biowin, CMAS or other sophisticated BNR simulation tools for design and analysis of specific treatment plant systems to better predict the process behavior. This process modeling software allows engineers to examine scenarios in wastewater treatment plants without making trial and error changes to operations that could be destructive to plant performance. This manual should provide some direction in examining trial and error scenarios in the software as well as providing some physical design improvements.

Instructions for manual use: This manual can be best utilized by reviewing the following figures for design improvements of interest, then reading the associated material for more detailed descriptions and quantifications. Additional improvements and specifically chemical feed improvements are noted at the end.
1. Add sugary waste to fermenter then to anaerobic zone to keep VFA’s at a minimum of 20 mg/l to promote phosphorus removal.

2. Turn off internal recycle during low flow periods when flow is 25% less than design and rely on RAS to provide oxygen, nitrates and nitrites to limit the free oxygen and allow a truly anoxic zone.

3. Reduce detention time to 30 minutes for lower flows than design.

4. Provide back up equipment for critical components such as pumps for RAS.

5. Automate RAS to be proportioned at 50-70% of the influent flow.

Figure 8 – Activated Sludge Process Improvements
6. Baffles constructed ½ inch below water surface elevation so foam can flow over the baffles.

7. Apply RAS at beginning for step feed so clarifiers are not overtaxed. Apply RAS immediately adjacent to or perpendicular to the influent flow to facilitate mixing.

8. A smaller SVI means the clarifier will have better settling. An SVI of 75 is good whereas 150 means there could be problems. If this is too high, the sludge blanket can rise and overflow. (25 lb/day of TSS per square foot of clarifier surface area is acceptable).

9. Do not add too much flow at the end of the aeration basins since this will allow less hydraulic residence time so flow could go by untreated and violate permits. 25% of flow added at four equally spaced apart locations is acceptable.

Figure 9 – Step Feed Activated Sludge Process Improvements
Improvement 1.

- A plant with insufficient VFA’s can be supplemented with acetic acid.
- A chemical feed line for acetic acid should be routed from the chemical feed tanks storing acetic acid to the location of feed.
- The optimum level of VFA’s is 15-20 mg/l. The exact amount of acetic acid required to maintain this level will include many variables and needs to be determined by a computer program such as CMAS or BioWin.
- Example: A 6mgd plant wants to keep VFA’s at 20mg/l.
  
  \[
  6\text{mgd} \times 20\text{mg/l} \times 8.34\text{ lb/gal} = 1000.8\text{ lb/day acetic acid} \\
  1000.8\text{ lb/day} \times 30\% \text{ acetic acid} / 8.84\text{ lb/gal} = 33.9\text{ gal per day of 30\% acetic acid chemical feed.}
  \]

Improvement 2.

- Internal recycle pumps should be designed to be turned off during the low load start-up.
- RAS can be used instead to provide enough nitrates/nitrites to maintain anoxic zone.

Improvement 3.

- BNR zones should be designed in treatment trains and flexibility allowed so some treatment trains can be offline during start-up.
• Detention times for anaerobic zone should be 30-45 minutes for design flow and no longer than 1 to 1 1/2 hours.

**Improvement 4.**

• Provide backup equipment for critical components. All pumps are critical and require an in-place back-up pump with all necessary piping and appurtenances online and able to be used with a turn of a valve.

• Consider routine and corrective maintenance procedures when laying out equipment to provide ample space for operator access.

**Improvement 5.**

• Recycle flows should be automated and flow paced based on the process influent flows.

• Return activated sludge (RAS) should be approximately 50%-70% of the influent flow

• Mixed liquor recycle back to the anoxic zone should be 2 to 4 times the influent flow.

• Discuss the automatic and local control schemes with the operations and maintenance staff prior to finalizing the specifications. This will allow a more user friendly control scheme.

**Improvement 6.**

• Construct baffles 6 inches below water surface elevation so foam can flow over.

• Foam can be directed to a foam pit where it can be pumped to solids handling.
Improvement 7.

- Step feed is useful when the land available is limited since more flow can get through a smaller basin.
- The influent flow is fed in many places but the return activated sludge (RAS) should be fed in one place, in the front of the biological nutrient removal basins so there is a longer sludge retention time.
- To provide optimal mixing of the RAS and influent, place the RAS immediately adjacent or perpendicular to the influent flow at a different elevation in the basin.

Improvement 8.

- A sludge volume index (SVI) of 100 or lower indicates sludge having good settling characteristics.
  - $\text{SVI} = \frac{(\text{settled sludge volume (ml/l)} \times 1,000)}{\text{MLSS (mg/l)}}$
- Clarifier Parameters:
  - Total suspended solids (TSS) = 25 lb/day/sqft
  - Average surface overflow rate = 700 gpd/sq ft based on the surface area of the clarifier.
  - The maximum surface overflow rate should be limited to 1,400 gpd/sq ft.
Improvement 9.

- Step feed is useful when the land available is limited since more flow can get through a smaller basin.
- Aeration basin step feed should be planned so there are 4 inputs of 25% of the flow spaced equally along the basin.
  - A concern with step feed is adding too much flow near the end of the basin since this allows less hydraulic residence time which could leave flow untreated.
CLIMATE IMPROVEMENTS

- Oversize aerations systems by 10% to allow increased aeration during warm weather to keep dissolved oxygen (DO) levels at 2 mg/l at all times.
  - Oxygen requirement can be converted to an airflow rate for diffused air systems by the following equation
    \[ A = \frac{95.2 \text{ DO}}{E} \]
    where
    \[ A = \text{Required air flow in cu ft/ min}, \]
    \[ \text{DO} = \text{Oxygen requirement, lb/hr}, \] and
    \[ T = \text{Oxygen transfer efficiency in the waste, percent}. \]

- BNR should be set up in treatment trains so that some trains can be offline until they are needed to help nitrify in cold weather. The retention times or tank sizes need to be doubled with every drop in 10 degrees Celsius below average design temperature.

CHEMICAL FEED IMPROVEMENTS

- Chemical feed lines of Alum need to be routed to the primary and final clarifiers with valves available for control to avoid spikes in phosphorus in the system. Amounts of alum required will need to be determined based on trial and error by computer program or operations staff and can be adjusted with the control valves.
• A lime silo with 30% lime slurry should be provided and routed into the primary clarifiers.
  - 7.14 mg CaCO3 / mg ammonia nitrified
  - Example: 6 mgd plant, 25-30 parts ammonia and 140 parts alkalinity.
    30 x 7.14 = 214 parts of alkalinity required to oxidize existing ammonia.
    60-100 parts of alkalinity are required to achieve a PH of 6-9 in effluent.
    100 + 214 = 314 parts of alkalinity required.
    Alkalinity must be increased from 140 parts in plant influent to 314 parts.
    314 – 140 = 174 parts CaCO3 required in 30% lime slurry.

• If the plant will have reduced capabilities during expansion construction due to treatment trains offline, provide approximately a 10,000 gallon tank of magnesium hydroxide near the influent pump station and trickle magnesium hydroxide into the influent to reduce the loading to match the plant capabilities. The exact amount of magnesium hydroxide required can be determined by use of a simulation software tool.
APPENDIX F – Human Subjects Research Approval Letter

The Federal Government and University Policy require that the use of human subjects in research be monitored by the Institutional Review Board (IRB). Appendix F contains a letter from the IRB approving the use of human subjects for this research.
May 21, 2004

K. Brile Zickefoose
Black & Veatch
8400 Ward Parkway
Kansas City, MO 64114-2031

Re: (04. 317) Improving Design of the BNR Process in Wastewater Treatment Plants from an Operations Perspective

Dear Ms. Zickefoose:

Your above-referenced application was reviewed at the May 12, 2004 Human Subjects Committee meeting. The Committee determined that you may use the data you collected during this study; however, the Committee cannot approve your project.

The federal regulations governing human subject protection at 45 CFR 46, and the Office of Human Research Protection ("OHRP") preclude us from approving studies wherein data has been collected prior to our committee review and approval. This assurance letter can be found at our webpage (http://www.research.fsu.edu/human subjects/assurance.html) and states in part:

"The involvement of human subjects in research covered by this Assurance will not be permitted until an appropriate IRB has reviewed and approved the research protocol and informed consent has been obtained from the subject or the subject's legal representative (see Sections 111, 116 and 117)"

We frequently request that researchers complete the NIH certification course in human subject protection. This on-line course will instruct you on the basic principles, regulations, and guidelines governing the use of human subjects in research, and requires approximately one hour of your time to complete. We strongly recommend that you complete the course, which is located at the following internet address: http://ohsr.od.nih.gov/cbl/cbl.html.

Please do not hesitate to contact me should you have any questions regarding this matter.

Sincerely,

John M. Tomkowiak, M.D.
Chair, FSU Human Subjects Committee

Cc: Danuta Leszczynska, Ph.D
(Department of Civil and Environmental Engineering)
BIBLIOGRAPHY


BIOGRAPHICAL SKETCH

K. Brie Zickefoose was born in Kansas City, Missouri and currently resides with her husband in Tallahassee, Florida.

EDUCATION

5/04 Master of Science in Environmental Engineering and Science
   Florida State University, Tallahassee, Florida

5/98 Bachelor of Science in Civil Engineering
   University of Kansas, Lawrence, KS

Professional Registration:
   Professional Engineer, FL, No. 60312

WORK EXPERIENCE

8/99 to present Black and Veatch, Greenville, South Carolina

5/98 – 8/99 Black and Veatch, Overland Park, KS

Staff engineer responsible for design, permitting and construction administration. Design projects including waste water treatment plants, transmission mains and reuse pipelines; permitting work including erosion and sedimentation control permit preparation; and construction phase services involving construction administration, review of shop drawings and operation and maintenance manuals.

5/97 – 5/98 Civil Engineering Intern and Part-time Employee
   Black and Veatch Pritchard, Overland Park, KS

5/95 – 5/98 Undergraduate Research Assistant
   University of Kansas, Lawrence, KS

HONORS & ASSOCIATIONS

Chi Epsilon, Civil Engineering Honor Society
Order of Engineer, Engineering Ethics Society