

---

# **NOTES ON ACTIVATED SLUDGE PROCESS CONTROL**

---

Prepared By: State of Maine  
Department of Environmental Protection

---

**2009**

## PREFACE

The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) established the National goals to restore and maintain the chemical, physical and biological integrity of the Nation's waters.

In August 1973, the US EPA published its definition of secondary treatment. Three major effluent parameters were defined: 5 day Biochemical Oxygen Demand (BOD<sub>5</sub>), total suspended solids (TSS) and pH. Secondary plants treating municipal wastewater are limited to 30 mg/L monthly average, 45 mg/L weekly average and 85 percent removal of BOD<sub>5</sub> and TSS.

The BOD determination involves the measurement of the dissolved oxygen used by microorganisms in the biochemical oxidation of organic matter. The BOD test bottle is incubated for 5 days at 20°C (see Laboratory Summary Appendix A). A typical BOD curve is shown in Figure P-1. The BOD<sub>5</sub> of secondary effluents consists of two major components – a carbonaceous demand resulting from the oxidation of carbon and a nitrogenous demand resulting from the oxidation of nitrogen. That is,

$$\text{BOD}_5 = \text{CBOD}_5 + \text{NBOD}_5$$

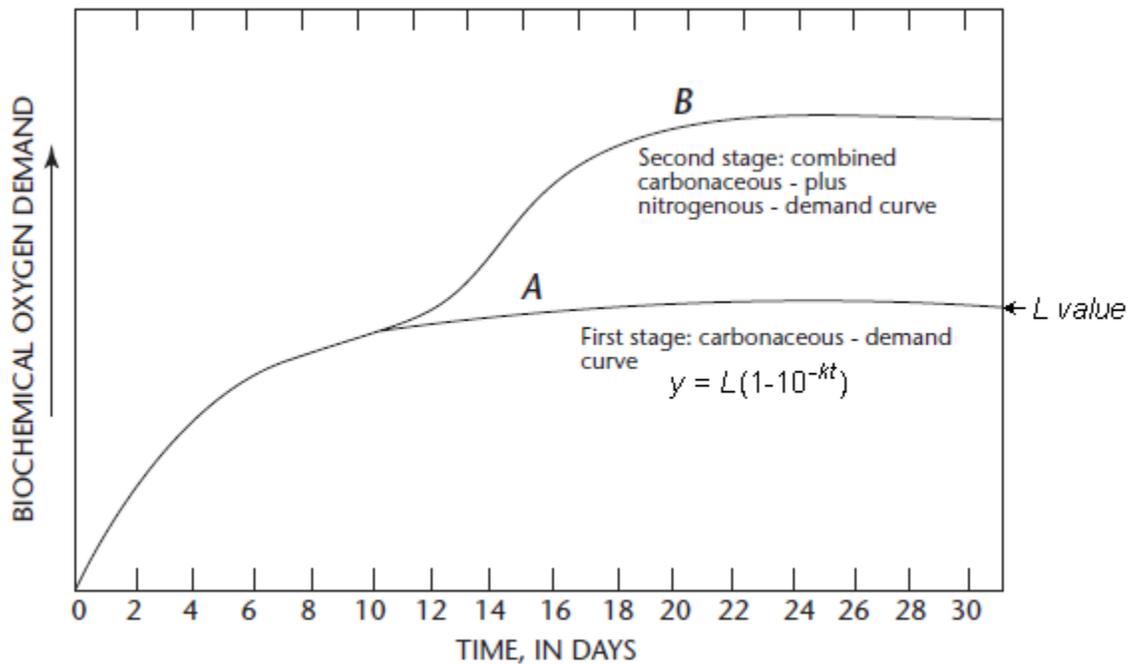


Figure P-1 The BOD curve, (a) Normal curve for oxidation of organic matter, (b) The influence of nitrification.

Total solids are defined as all the matter that remains as residue upon evaporation at 103 to 105°C. Total solids can be classified as either suspended solids or filterable solids by passing a known volume of liquid through a filter. The filter is commonly chosen so that the minimum diameter of the suspended solids is about 1 micron. The suspended solids fraction includes the settleable solids that will settle to the bottom of a cone shaped container (called an Imhoff cone) in a 60 minute period and those solids which are retained on a filter and heated for one hour at 103-105°C (see Figure P-2).

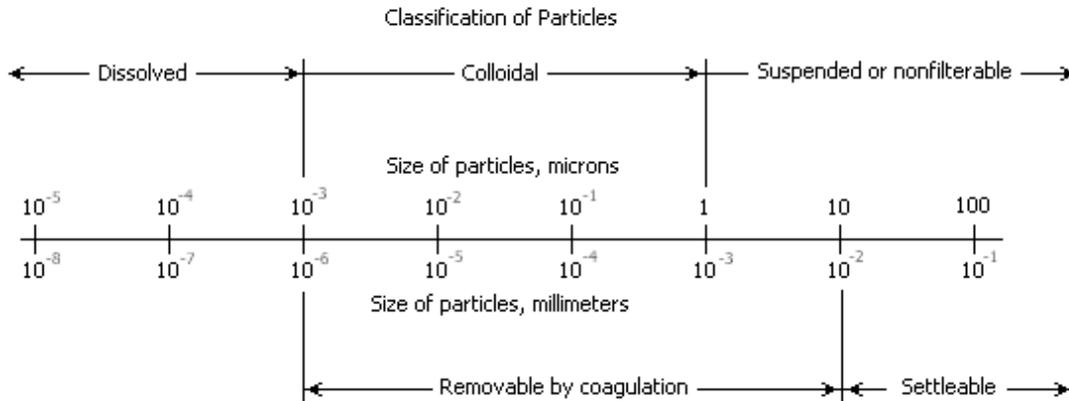


Figure P-2 Classification and size range of particles found in wastewater.

The measure of pH is the hydrogen ion concentration. pH is used to express the intensity of the acid or alkaline condition of a solution. The scale of pH ranges from 0 to 14, with 7 being neutral. The effluent limit for pH is typically 6 to 9.0

There are four major biological processes used for wastewater treatment. These four major groups are: aerobic process, anoxic processes, anaerobic processes and a combination of the aerobic/anoxic or anaerobic. The aerobic processes include suspended growth process (such as activated sludge and aerated lagoons) and attached growth facilities which include trickling filters and Rotating Biological Contactors (RBCs). Maine has about 70 activated sludge treatment plants, 17 aerated lagoons, nine RBCs, two trickling filters and two activates biolfilter (a combination of tricking filter and activated sludge) plants.

The objectives of the activated sludge wastewater treatment plants are to coagulate and remove the nonsettable colloidal solids and to stabilize the organic matter.

The purpose of activated sludge wastewater treatment plants was to accelerate the forces of nature under controlled conditions in treatment facilities of comparatively small size.

In the removal of carbonaceous BOD, the coagulation of nonsettleable colloidal solids and the stabilization of organic matter are accomplished biologically using a variety of microorganisms, principally bacteria.

The microorganisms are used to convert the colloidal and dissolved carbonaceous organic matter into various gases and cell tissue.

Because the cell tissue has a specific gravity slightly greater than that of water, the resulting tissue can be removed from the treated liquid by gravity settling.

Studies in the early 1980's by the United States Environmental Protection Agency (EPA), the Water Pollution Control Federation (WPCF), and the General Accounting Office (GAO), indicate that 50 percent or more of the wastewater treatment facilities nationwide were failing to meet their discharge permit requirements. Those reports cited the lack of adequate training for operators as a major factor limiting the performance of these facilities.

Congress acknowledged the need for improvements in operator training programs and through the use of add-on funds in Section 104 (g)(1) of the Clean Water Act directed EPA to make grants to State training centers and agencies to provide on-site, over-the-shoulder training. The State of Maine has received Section 104(g)(1) funds for over twenty years.

The State of Maine's legislature also recognized the need for operator training and established the Joint Environmental Training Coordinating Committee (JETCC) to provide state-wide training opportunities.

Notes on Activated Sludge Process Control was started in the spring of 1987 by the DEP's Operation and Maintenance Division to served as a training resource for JETCC and during 104(g)(1) on-site training. It soon became evident that a set of notes was necessary to enable the person receiving the training to concentrate on the fundamental concepts without fear of missing the details. This collection of notes was prepared for use by wastewater treatment plant operators as a reference to help improve activated sludge plants performance through increased understanding of process control principles.

After over 20 years of experience providing training and technical assistance this collection of notes was updated in 2009 by the staff of the Maine Department of Environmental Protection, Division of Water Quality Management.

## TABLE OF CONTENTS

|                         |   |
|-------------------------|---|
| PREFACE .....           | i |
| TABLE OF CONTENTS ..... | 1 |
| LIST OF FIGURES .....   | 2 |

### SECTION

|   |    |
|---|----|
| I. INTRODUCTION .....                               | 3  |
| II. FUNDAMENTALS.....                               | 3  |
| III. MICROORGANISMS.....                            | 15 |
| IV. ACTIVATED SLUDGE PROCESS MODIFICATIONS .....    | 18 |
| V. SOLIDS ACCUMULATION.....                         | 22 |
| VI. COMPLETE MIX ACTIVATED SLUDGE EQUATIONS .....   | 28 |
| VII. SOLIDS SEPARATION.....                         | 32 |
| VIII. SOLIDS FLUX THEORY .....                      | 35 |
| IX. MASS BALANCE.....                               | 42 |
| X. NITRIFICATION .....                              | 46 |
| XI. PROCESS CONTROL – WHAT CAN BE CONTROLLED? ..... | 52 |
| XII. AERATION RATE CONTROL.....                     | 54 |
| XIII. RETURN SLUDGE RATE CONTROL .....              | 58 |
| XIV. WASTE ACTIVATED SLUDGE CONTROL .....           | 64 |
| XV. PROCESS MONITORING .....                        | 70 |
| XVI. TROUBLESHOOTING.....                           | 76 |
| XVII. GLOSSARY .....                                | 84 |

### APPENDIXES

|   |  |
|---|--|
| A. LABORATORY SUMMARY                                       |  |
| B. DESIGN AND OPERATING PARAMETERS                          |  |
| C. THE MICROBIOLOGY OF ACTIVATED SLUDGE                     |  |
| D. ACTIVATED SLUDGE MICROBIOLOGY PROBLEMS AND THEIR CONTROL |  |
| E. NUTRIENT DEFICIENCY CALCULATIONS                         |  |
| F. RETURN CHLORINATION (BULKING) CALCUALTIONS               |  |
| G. SETTLEABILITY TEST PROCEDURES                            |  |
| H. OUR TEST PROCEDURES                                      |  |
| I. MICROSCOPIC TEST PROCEDURES                              |  |
| J. ACTIVATED SLUDGE OBSERVATIONS                            |  |
| K. ORP RANGES   |  |
| L. CORE-TAKER PROCEDURES                                    |  |
| M. MCRT RELATIONSHIP TO F/M                                 |  |
| N. FINAL CLARIFIER SOLIDS FLUX                              |  |
| O. TROUBLESHOOTING CHARTS                                   |  |
| P. TROUBLESHOOTING ACTIVATED SLDUGE PROCESSES               |  |
| Q. NITRIFICATION SRT CALCULATIONS                           |  |
| R. PROCESS CONTROL CALCULATIONS                             |  |
| S. WET WEATHER OPERATING PLAN                               |  |
| T. SAMPLE MANUAL OF OPERATIONS                              |  |
| U. MICROBIOLOGY FOR WASTEWATER TREATMENT PLANT OPERATORS    |  |
| V. ALKALINIATY AS A PROCESS CONTROL INDICATOR               |  |

## LIST OF FIGURES

| Number  | Page |
|---|------|
| P-1 The BOD curve .....   | i    |
| P-2 Classification and size range of particles found in wastewater..... | ii   |
| 1.01 Bacteria cell metabolism .....                                     | 4    |
| 2.01 Synthesis and oxidation of organic matter .....                    | 7    |
| 2.02 Energy conversion .....  | 9    |
| 2.03 SVI versus sludge age .....  | 11   |
| 2.04 Sludge settleability vs. organic loading .....                     | 12   |
| 2.05 Growth curve .....   | 13   |
| 4.01 Basic activated sludge process diagram .....                       | 19   |
| 4.02 Mixing regime and flow variations .....                            | 21   |
| 5.01 Derivation of F/M & MCRT Relationship .....                        | 24   |
| 5.02 Organic load vs. solids production .....                           | 25   |
| 5.03 Sludge age vs. solids production .....                             | 25   |
| 6.01 Mixed Liquor Suspended Solids vs. sludge age .....                 | 31   |
| 7.01 Solids concentration vs. settling type .....                       | 33   |
| 7.02 Zone settling rate .....   | 34   |
| 8.01 Flux resulting from gravitational settling .....                   | 36   |
| 8.02 State point analysis .....   | 39   |
| 8.03 Variations in influent flow .....                                  | 40   |
| 8.04 Effects of recycle rate changes .....                              | 41   |
| 8.05 Effects of an increase in MLSS .....                               | 43   |
| 8.06 Effects of sludge settling characteristics .....                   | 44   |
| 10.01 Wastewater nitrogen cycle .....                                   | 51   |
| 11.01 Relationship between physical limitations and operations .....    | 53   |
| 11.02 Diagram of typical activated sludge plant .....                   | 55   |
| 11.03 Relationship of proper environment and process control .....      | 56   |
| 13.01 Three types of sludge settleability .....                         | 63   |
| 15.01 Process control test location .....                               | 76   |
| 16.01 Diagram of the troubleshooting process .....                      | 80   |

## I. INTRODUCTION

The activated sludge treatment process was developed in England during the early 1900's. In 1914, H.W. Clarke at the Lawrence Experimental Station, Massachusetts, studied sewage purification through its aeration in the presence of microorganisms. Dr. G.S. Fowler (Consulting Chemist, Rivers Committee of Manchester Corporation) during a visit to the United States observed some of the Lawrence experiments and suggested to Edward Arden and William Lockett (Davyhulme Sewage Works, Manchester Corporation) that they carry out similar experiments. Arden and Lockett achieved high purification levels through the use of an aeration process, which incorporated the recovery of flocculent solids and their recycle to the aeration stage. Thus, was the activated sludge method of wastewater treatment born.

Many people feel that the activated sludge process cannot be controlled and will not perform reliably. Assuming that the plant is adequately designed, properly maintained and operated, the activated sludge process can and does produce an excellent effluent. Whenever plant operation or, more specifically, process control is discussed, five questions are very important:

1. What is the process to be controlled?
2. What can be controlled?
3. What are the control strategies?
4. What should be monitored?
5. How do we troubleshoot the process?

These "Notes on Activated Sludge Process Control" are organized to answer these five questions.

## II. FUNDAMENTALS – What is the process to be controlled?

Stated in fundamental terms, the activated sludge process simply involves bringing together wastewater and a mixture of microorganisms under aerobic conditions. The process is a combination of:

- the natural breakdown of organic matter by *biological metabolism* and
- the separation of the solids and liquids by *bioflocculation* and the natural force of gravity.

Activated sludge, therefore, serves two purposes:

1. Reducing organic matter in wastewater by using a complex biological community in the presence of oxygen and converting the organic matter to new cell mass, carbon dioxide and energy; and,
2. Producing solids capable of bio-flocculating and settling out in the clarifier to produce an effluent low in Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS).

Activated sludge is formed in three distinct steps:

1. Transfer step
2. Conversion step
3. Flocculation step

During the transfer step (see Figure 1.01), soluble organic matter is absorbed through the cell wall and into the cell where it is converted. Insoluble matter is adsorbed onto the cell wall and broken down and then absorbed through the cell wall.

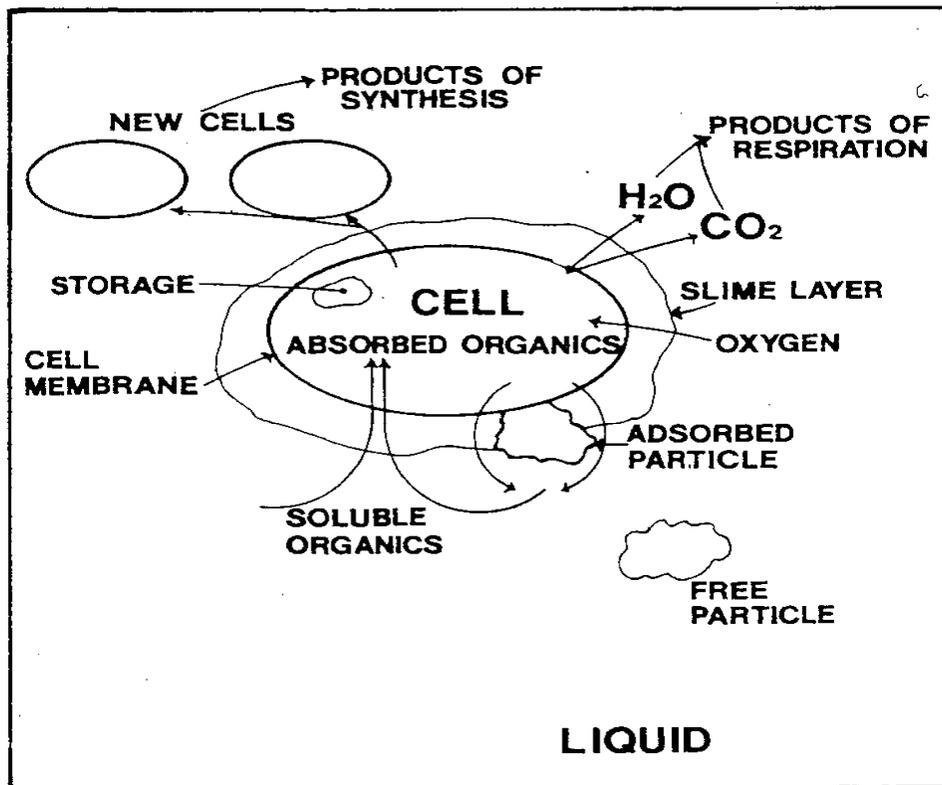


Figure 1.01

Before cell respiration and synthesis reactions can take place, the organic material (soluble or non-settleable particles) must be taken inside the bacterium. This proceeds in the following manner. First, the external food source comes into contact with the bacterial cell capsular layer (slime layer). The cell capsular layer provides elementary cell protection and serves as a depository for both food and waste materials.

Next, the food source reaches the cell wall. The cell wall has been likened to the steel girders of a building. It provides the cell with its basic shape and as a building's steel framework has openings in it as does the cell wall. These openings allow food to "pass" through the cell's semi-permeable membrane.

It is here that two things can occur:

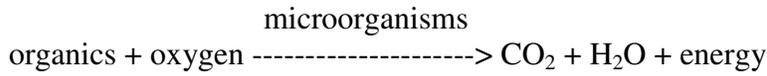
1. The food can pass through this membrane to the interior of the cell for utilization without any action by the cell to obtain it (passive transport); or
2. The food can be carried across the semi-permeable membrane (active transport). In this system the cell produces an enzyme (permease) that passes through the membrane and attaches to the food. This allows a food that may otherwise be unable to cross through the semi-permeable membrane to be utilized. The enzyme acts as a catalyst and is not changed in the transfer of food. Once the food is in the interior of the cell the enzyme becomes detached and is able to go back for more food. The permeases produced by cells are specific to certain substrates. Consequently, if the food cannot be utilized by one cell, it passes from cell to cell until one utilizes it or it passes out the effluent. This is why a biological system must be acclimated and why a varied group of microorganisms is required to breakdown a complex mixture of organic matter such as wastewater.

The conversion step is the second step towards the formation of activated sludge. The conversion step includes oxidation and synthesis. These two reactions make up the metabolic process. Metabolism is a life process involving a series of reactions in which some molecules are broken down and others are being formed. Metabolism can be divided into two parts: anabolism, or reactions involving the synthesis of compounds, and catabolism, or reactions involving the breakdown of compounds. Essential protein molecules which catalyze biochemical reactions are called enzymes. Some enzymes are within the cell (endocellular) and some are secreted to the outside (exocellular). For a cell to grow and reproduce it requires a source of energy and carbon for the synthesis of new cells. If an organism derives its cell carbon from carbon dioxide it is called autotrophic. If it uses organic carbon it is called heterotrophic. Respiration is the process of deriving usable energy from high energy molecules. Bacteria capture and store energy in the chemical bonds of "energetic" compounds such as adenosine triphosphate (ATP). ATP is built up in special structures within the cells called mitochondria.

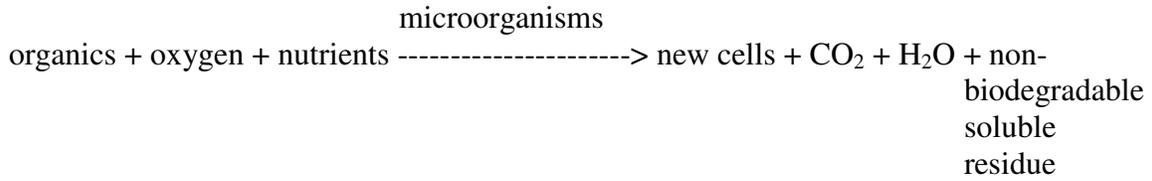
The reactions which take place during respiration are called oxidation-reduction. This involves the transfer of one or more electrons between two atoms. The first step involves the loss of an electron and is called an oxidation reaction while the second step involves the gain of an electron and is called a reduction reaction.

The biodegradation of organic matter found in wastewater by microorganisms has been viewed as a three-phase process with a portion of the removed organic matter being oxidized to supply energy and a portion being synthesized to new cells together with a subsequent oxidation of the new cells. These reactions can be illustrated by the following equations:

**Oxidation**



**Synthesis**



**Endogenous Respiration**

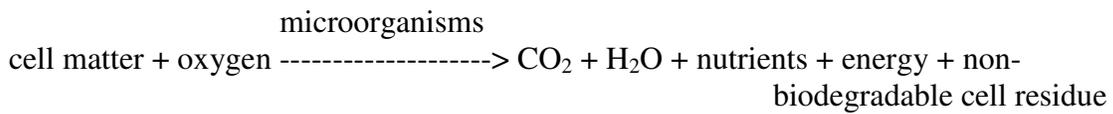


Figure 2.01 further illustrates the synthesis and oxidation of organic matter by microorganisms and the subsequent endogenous respiration.

The amount of food energy used for energy versus synthesis in the synthesis reaction is dependent on the composition of the organic matter metabolized. In domestic sewerage about one-third of the food (organic matter) yields energy and two-thirds of the food yields new cells.

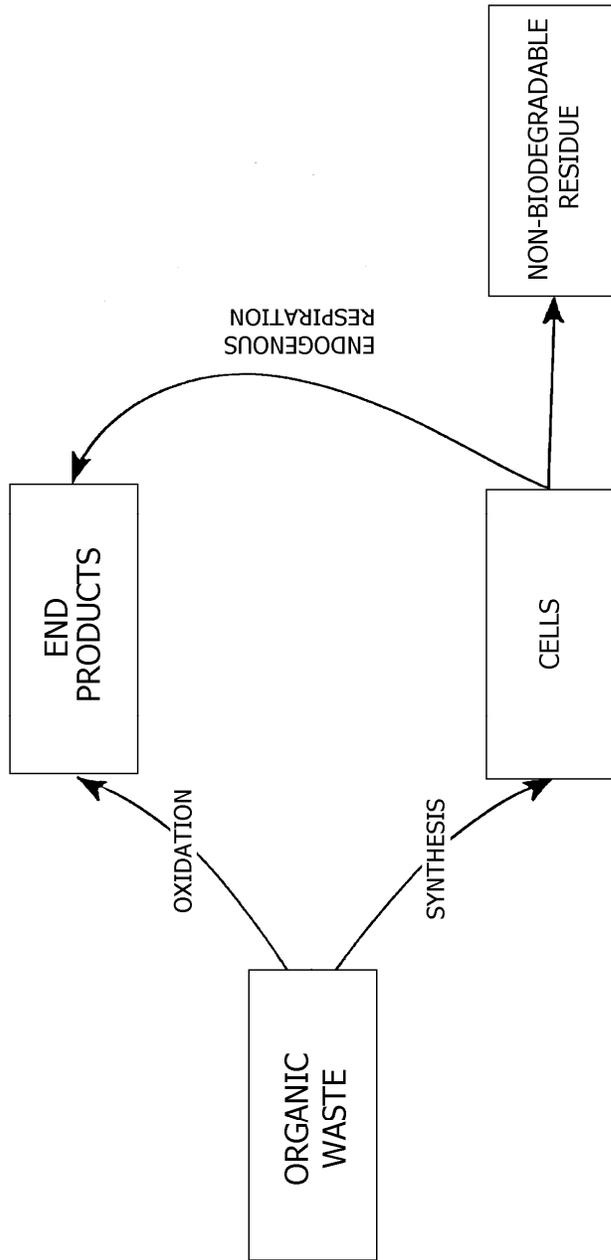
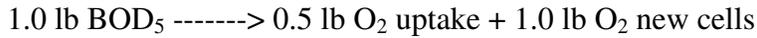


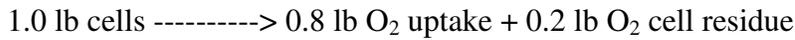
Figure 2.01

Therefore, in the synthesis reaction:

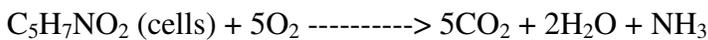


(Note: 1.0 lb BOD<sub>5</sub> = 1.5 lb BOD<sub>u</sub>)

In the endogenous respiration reaction:



Since,



MW=113      MW=160

$$\frac{160}{113} = 1.42 \text{ lb O}_2/\text{lb SS}$$

The extreme possible oxygen requirements and solids production are:

|                           | Oxygen Required<br>(lb O <sub>2</sub> /lb BOD <sub>5</sub> removed) | Solids Production<br>(lb SS/lb BOD <sub>5</sub> removed) |
|---------------------------|---|--|
| Synthesis                 | 0.5   | 0.7  |
| Endogenous<br>Respiration | 1.3   | 0.14   |

Figure 2.02 further illustrates the energy conversion.

Although it is important for bacteria to utilize the available substrate in wastewaters as efficiently as possible, it is also necessary to form solids that can be easily separated from the liquid in the final clarifier. The third step in the formation of activated sludge is the flocculation step.

This bio-flocculation or floc-formation is not totally understood, however, it is believed to result, in part, from the production of extra cellular polymers (polysaccharides) by the cells as the cell age increases. Eventually, the cell becomes encapsulated in this slime layer, which then helps promote the formation of bacterial floc particles by enabling the individual bacteria cells to “stick” together. As cells in the sludge age and die, the floc can break-up and new cells attach. However, if there are too many “old” cells in the floc (a high sludge age), it becomes difficult to get good floc formation and we get a turbid effluent. If, however, the bacterial cells grow too fast (a low sludge age) the cell surface area increases more quickly than the ability for the cell to cover it with a good slime layer, consequently, a low density floc with a lot of entrapped water develops, and it separates poorly from the liquid in the final clarifier.

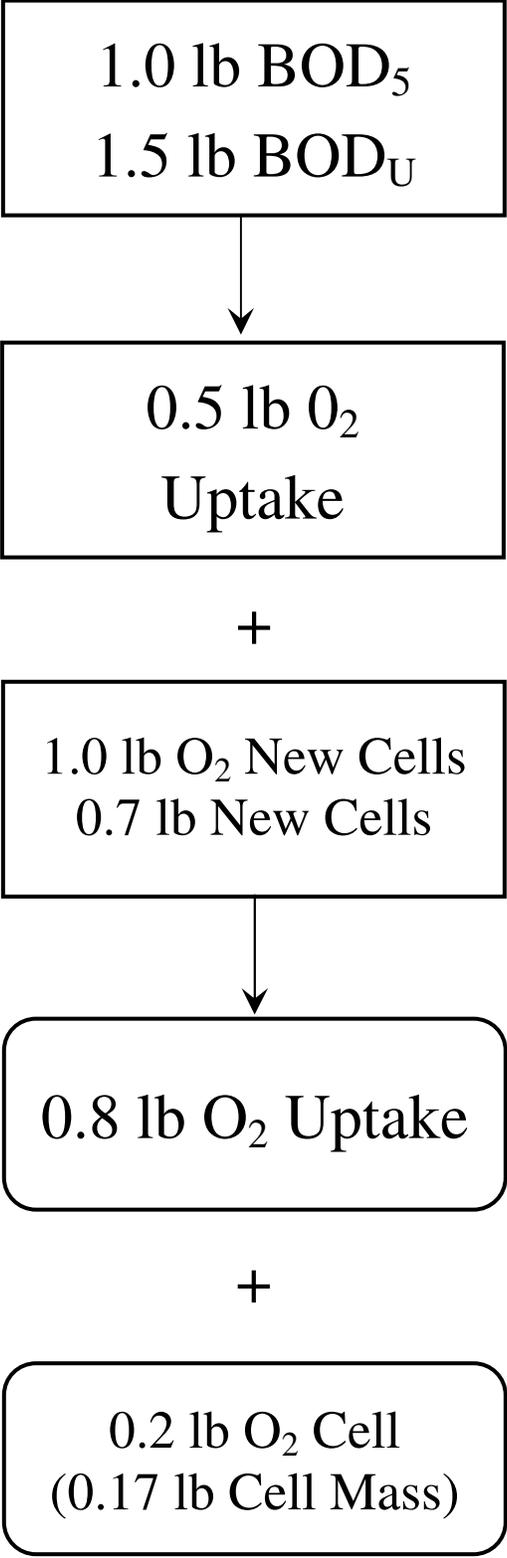


Figure 2.02

Therefore, an optimum “sludge age” exists which provide an adequate separation of the cell mass from the liquid. For a specific system the optimum sludge age can be determined by plotting the sludge volume index (SVI) versus the sludge age (see Figure 2.03). Figure 2.04 shows the SVI versus the F:M ratio.

In order to better understand the activated sludge process, which normally runs in a continuous flow mode, it is beneficial to first look at the process in a batch operation. This is done by taking a container of biologically degradable wastewater and aerating it with an air stone to provide sufficient oxygen and mixing energy. Measuring the number of microorganisms at constant time intervals, and plotting these numbers versus time, we get what is known as the growth curve. The growth curve has five distinct phases (see Figure 2.05).

These are:

1. Adaptation (Lag) Phase – This portion of the curve represents the time required for the organisms to acclimate themselves to the organic material present in the wastewater. The numbers of bacteria are not increasing, however, a shift in the population of the different species of bacteria in the wastewater is occurring so that the bacteria that can best utilize these organic materials become predominate.
2. Log Growth Phase – Once the bacteria have “adapted”, only the number of organisms present limit the rate of growth. Because bacterial cells reproduce by binary fission (i.e., cell division – one cell divides and becomes two, these two divide and become four, then eight, sixteen ... ), this is known as logarithmic growth. Food is not a limiting factor for growth in this phase, that is, for each cell formed enough food is present to allow it to grow and divide.
3. Declining Growth Phase – In this phase food becomes a limiting factor to the growth of the bacterial cell mass because not every bacterium that is formed has the food required to grow.
4. Maximum Stationary Phase – Here the available food is just sufficient to keep the cell mass at a constant level with a rate of growth equal to zero.
5. Endogenous (Cell Death) Phase – When the supply of food becomes insufficient to maintain the bacterial mass at a constant level, the microorganisms are forced to metabolize their own protoplasm.

Microorganisms may be classified according to the source of their energy and carbon requirements. Chemolithotrophs oxidize inorganic substances for their energy needs, whereas, chemoorganotrophs oxidize organic substances for their energy. Heterotrophs use organic substances as a carbon source for making cell materials, whereas, autotrophs use carbon dioxide as the source of carbon. Most of the microorganisms in activated sludge are chemoorganotrophic and heterotrophs.

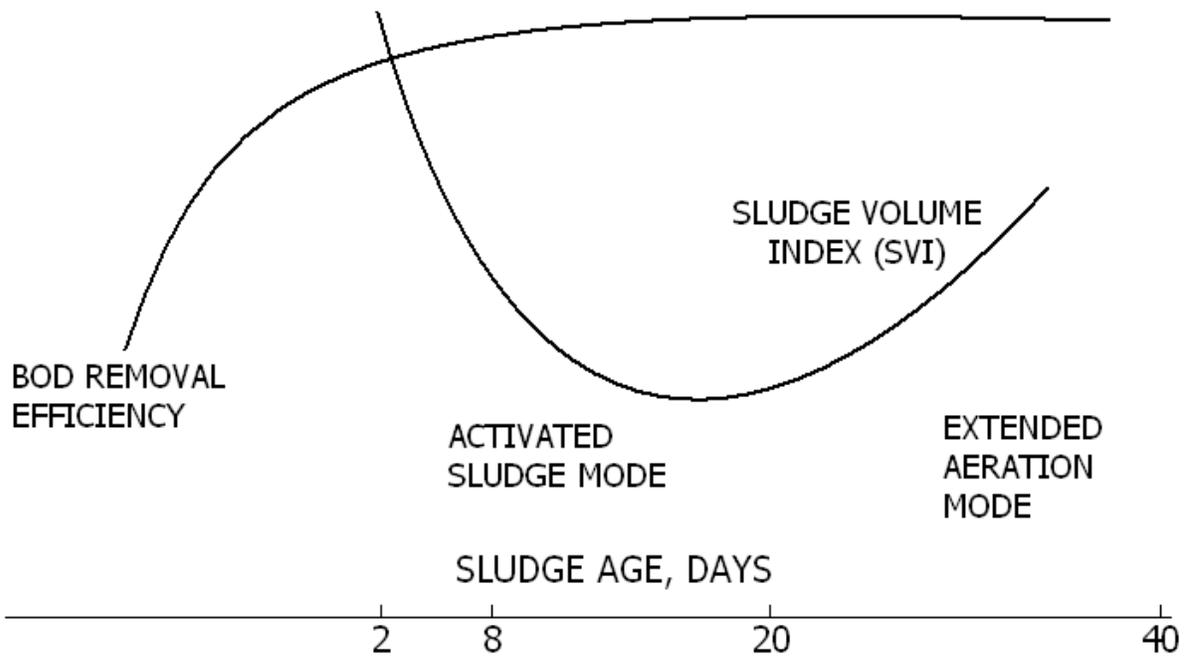


Figure 2.03

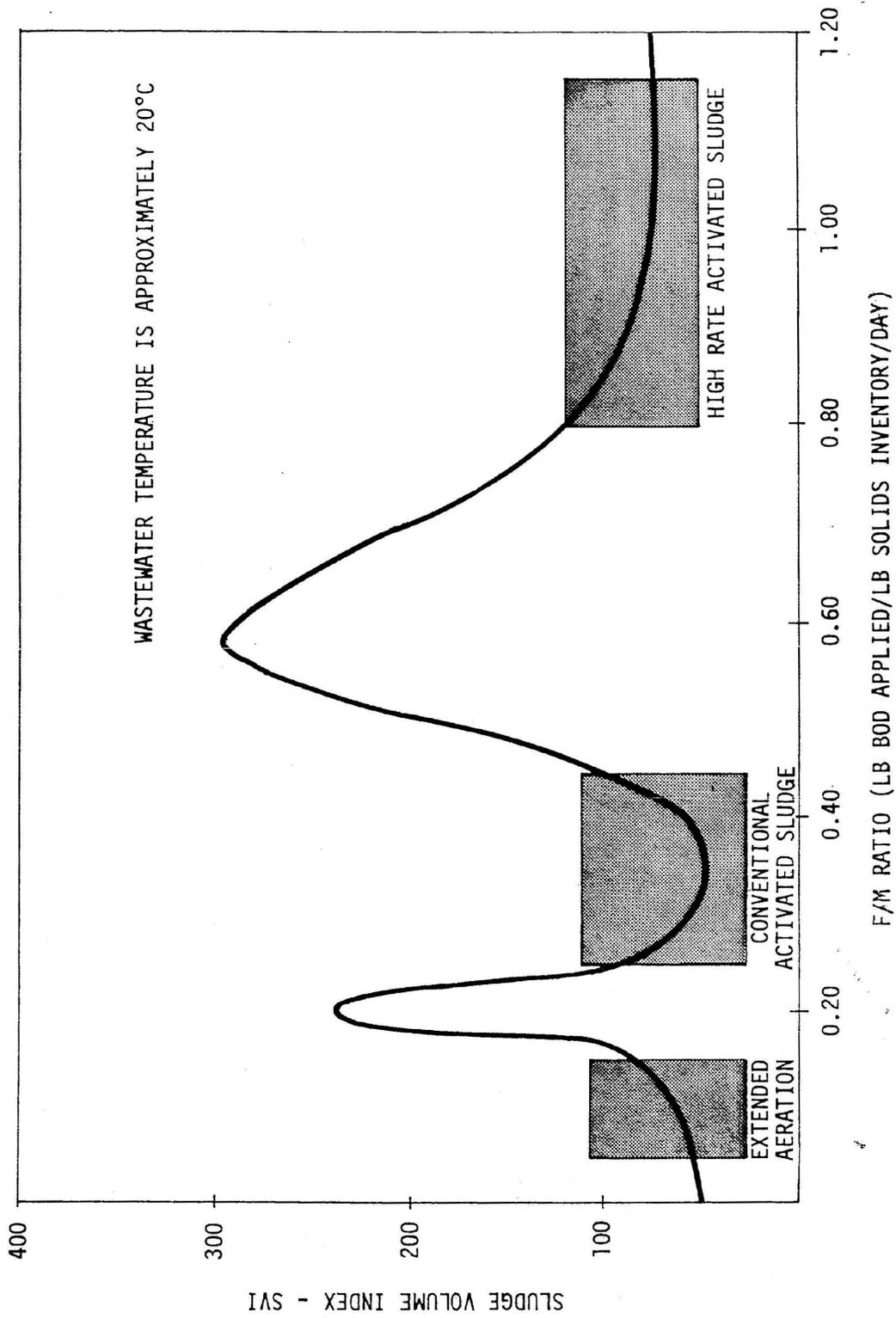


Figure 2.04

## GROWTH PHASES OF MICROORGANISMS

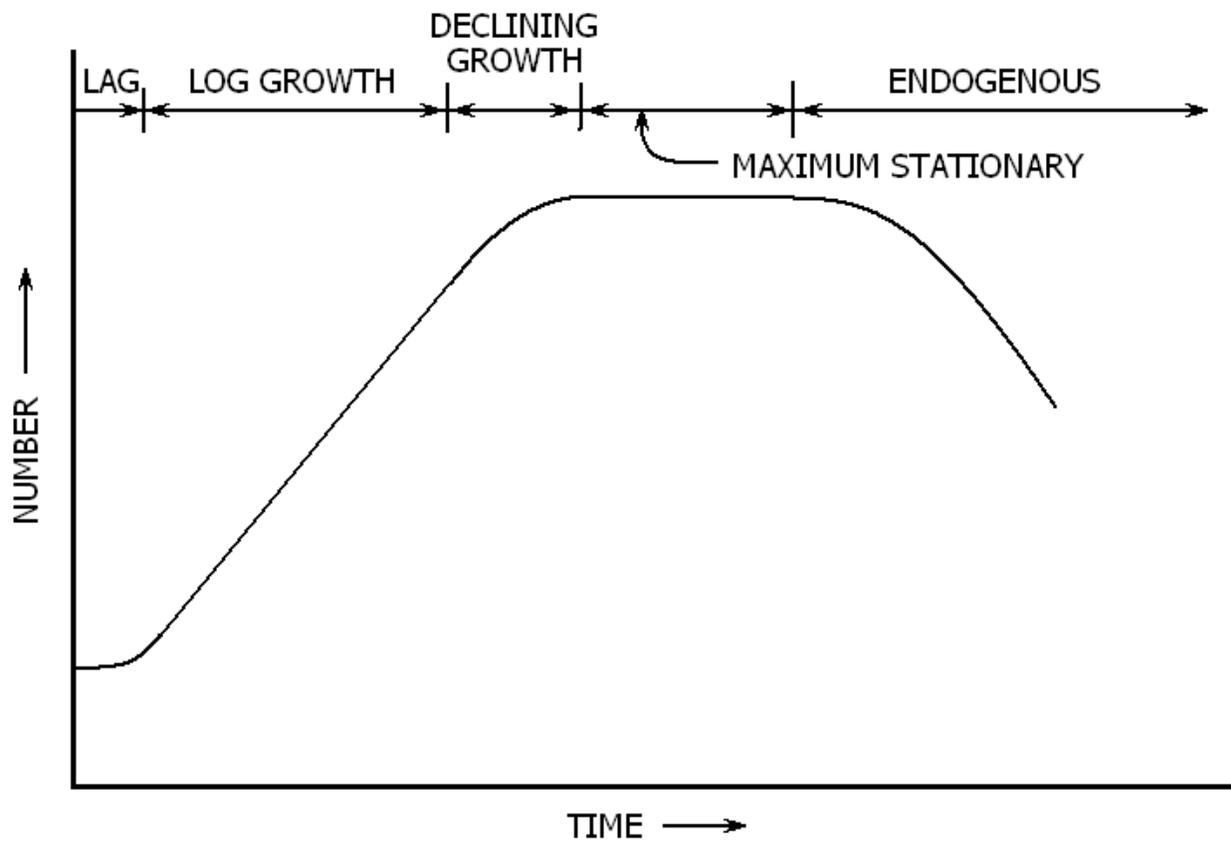


Figure 2.05

There are essential elements required for nutrition and they are often classified as 1) major elements, 2) minor elements, 3) trace elements and 4) growth factors.

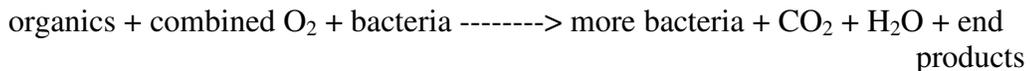
The major elements are carbon, hydrogen, oxygen, nitrogen and phosphorus. The minor elements are sulfur, potassium, sodium, magnesium, calcium and chlorine. The trace elements are principally iron, manganese, cobalt, copper, boron, zinc, molybdenum and aluminum. The growth factors include vitamins and amino acids. Generally, in municipal wastewater all of the essential elements and growth factors are present. Some industrial wastewaters may be deficient in nitrogen or phosphorus. As a general rule of thumb, 5 pounds of nitrogen and 1 pound of phosphorus are required for each 100 pounds of BOD removed.

Another important classification of microorganisms pertains to their respiration requirements. Microorganisms may be classified as aerobic, anaerobic or facultative.

In aerobic respiration the hydrogen (or electron) acceptor is molecular oxygen and the end product is water.



In anoxic and anaerobic respiration, the hydrogen (or electron) acceptor is combined oxygen in the form of radicals (carbonate, nitrate, sulfate and organic compounds) and the end products (for anaerobic respiration) are methane, ammonia, hydrogen sulfide or a reduced organic compound.



The table below shows the energy released during aerobic, anoxic and anaerobic respiration. As can be seen, more energy is released during aerobic respiration, therefore, biochemical reactions will take precedence in the order of most to least energy released.

| Electron Acceptor | By-products      | Energy Released |
|-------------------|------------------|-----------------|
| O <sub>2</sub>    | CO <sub>2</sub>  | 25.3 kcal       |
| Nitrate           | N <sub>2</sub>   | 23.7 kcal       |
| Sulfate           | H <sub>2</sub> S | 1.5 kcal        |
| CO <sub>2</sub>   | CH <sub>4</sub>  | 0.9 kcal        |

All organisms naturally seek conditions yielding the greatest amount of energy for their life processes.

There are several environmental factors that affect microbial activity. They may be classified as physical, chemical or biological. Three of the important physical factors are temperature, osmotic pressure and oxygen/mixing.

Temperature has a tremendous effect on the rate of cell growth. An increase in temperature of 10°C (within the range of temperature that bacteria can grow) can approximately double the rate of cell growth and substrate utilization. Microorganisms may be classified according to their optimum temperature range as psychrophils, mesophils, and thermophils, which have respective optimum temperature ranges of 0 to 10°C, 10° to 45°C and 45° to 75°C.

Because microorganisms feed by osmosis, the osmotic pressure, which is dependent upon the salt concentration, must be within a certain range. Most microbes are not affected by salt concentrations between 500 to 35,000 mg/L. In general, a dissolved oxygen of 1.0 to 2.0 mg/L is best for maintaining efficient, healthy microorganisms. If the D.O. drops below 1.0 mg/L, and especially below 0.5 mg/L, aerobic treatment efficiency will suffer. A well-mixed aeration basin will keep the microorganisms in suspension and increase the contact of the microbes with the food source.

The major chemical factors are 1) pH, 2) the presence of acids and bases, 3) the presence of oxidizing and reducing agents, 4) the presence of heavy metals, and 5) certain chemicals.

The pH of the wastewater is important because bacteria grow best in a pH range of 6 to 9. Outside of this range bacterial growth is inhibited. Bacteria can acclimate to long term changes in pH and to a certain degree they can buffer the wastewater against variations in pH because of the production of CO<sub>2</sub> in the oxidation of organic matter. However, rapid changes have severe detrimental impacts on bacterial growth. Toxic substances, (e.g., phenol, chlorinated hydrocarbons, heavy metals, halogens, acid and bases, etc.) inhibit cell growth and substrate utilization even at very low concentrations. In general, the toxicity of metal ions increases with an increase in atomic weight.

### III. MICROORGANISMS

The principal microorganisms involved in the breakdown of organic matter in wastewater are single-celled bacteria. Other microorganisms of importance in biological treatment are: fungi, algae, protozoa, rotifers and nematodes. The predominant species are determined by the characteristics of the influent, the environmental conditions, process design and mode of operation.

Bacteria are small (0.5 – 1.0 microns by 1.0 – 5.0 microns), single-celled protista. They grow in many shapes: round, rod, spiral, comma or budding. They are either aerobic, anoxic or anaerobic. The majority of the bacteria in activated sludge are facultative, that is, they can live in either aerobic or anoxic conditions. The bulk of the bacteria in activated sludge prefer the pH to be between 6.5 and 9.0. Bacteria adsorb to soluble and particulate wastewater solids and produce enzymes that break down those solids into

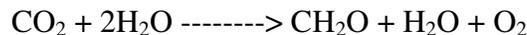
nutrient forms that can be absorbed into the cell. Floc-forming bacteria produce compact flocs which settle well. Filamentous bacteria grow in either an open or bridging floc structure. It is important for a strong floc to have some filaments growing through it to act as a backbone. Excessive growth of filaments is known as filamentous bulking.

Floc-forming and filamentous bacteria compete for food, oxygen and nutrients, but differ in the way they metabolize these compounds. Floc-forming bacteria prefer short duration, high doses of food whereas filamentous bacteria prefer steady low doses. Floc-forming bacteria can survive and, in some cases, prefer alternating aerobic and anoxic conditions whereas some filamentous bacteria prefer low concentrations of dissolved oxygen.

Fungi are multicellular, non-photosynthetic, heterotrophic protista. They are strict aerobes and must have free dissolved oxygen. They predominate at low nitrogen levels and/or low oxygen levels and grow well at pH values under 6.0.

Algae are unicellular or multicellular autotrophic, photosynthetic protista. They are more important in lagoons than in activated sludge treatment plants. However, an understanding of the biochemical reactions for photosynthesis and respiration can be beneficial.

#### Photosynthesis



#### Respiration



Protozoa are motile single cell protists. They are several hundred microns in size, tend to be strict aerobes and are more sensitive to toxic materials. There are many types of protozoa: amoebae, flagellates, free-swimming ciliates, and stalked ciliates, each working in its own niche in the biological scheme.

Amoebae are single cells of protoplasm that move slowly in search of food by pushing protoplasm into areas within the cell membrane called pseudopodia, or false feet. The testate amoebae are usually associated with nitrified conditions where little unionized ammonia exists.

Flagellated protozoa are very small and propel themselves using a whip-like appendage called a flagella. Since they move quickly, their energy requirements are much higher than amoebae or bacteria. Flagellates predominate when bacteria are dispersed and upon recovery from a toxic spill.

Free-swimming ciliates are much larger and move around using tiny hair-like structures called cilia. Bulk liquid free-swimmers are found in poorer effluent conditions and in

activated sludge systems that yield turbid effluents. Crawlers are found in medium aged activated sludge and are usually associated with better effluent quality.

The stalked ciliates are very energy efficient and are found in high numbers in effluents of very good quality.

Rotifers are much larger multicellular animals which are generally strict aerobes.

Nematodes and annelids (bristle worms) are multicellular worms. Nematodes occur in higher sludge age systems. Bristle worms (and water bears) occur in nitrifying systems.

#### IV. ACTIVATED SLUDGE PROCESS MODIFICATIONS

The basic activated sludge process has several interrelated components. These components are (see Figure 4.01):

1. aeration tank
2. aeration source
3. clarifier,
4. recycle, and
5. waste

**Aeration tank.** A single tank or multiple tanks designed generally for either complete mix or plug flow with a detention time of as little as 2 hours and up to over 24 hours. The contents of the aeration tank are referred to as mixed liquor.

**Aeration source.** Generally either diffused air or surface mechanical aeration used to supply oxygen and mix the aeration tank contents.

**Clarifier.** A settling tank where the mixed liquor solids are separated from the treated wastewater. Most treatment plants employ several secondary clarifiers.

**Recycle.** Solids that settle in the clarifier and are returned to the aeration tank.

**Waste.** Excess solids that must be removed from the system.

There are three classic variations of the activated sludge process – high rate, conventional rate, and extended aeration (see Appendix B).

High rate systems have short-term aeration times (2-4 hours) and higher F:M ratios. These systems must be operated more carefully because the shorter aeration times make the system more sensitive to washouts.

Conventional is used to define a system of intermediate loading. Plants operating in the middle range do not nitrify.

Extended aeration plants are characterized by long aeration time (24 hours), high mixed liquor concentrations, high sludge retention times, total oxygen requirements are higher and nitrification may occur. The losses of pin floc and heat are common problems.

# ACTIVATED SLUDGE FLOW DIAGRAM

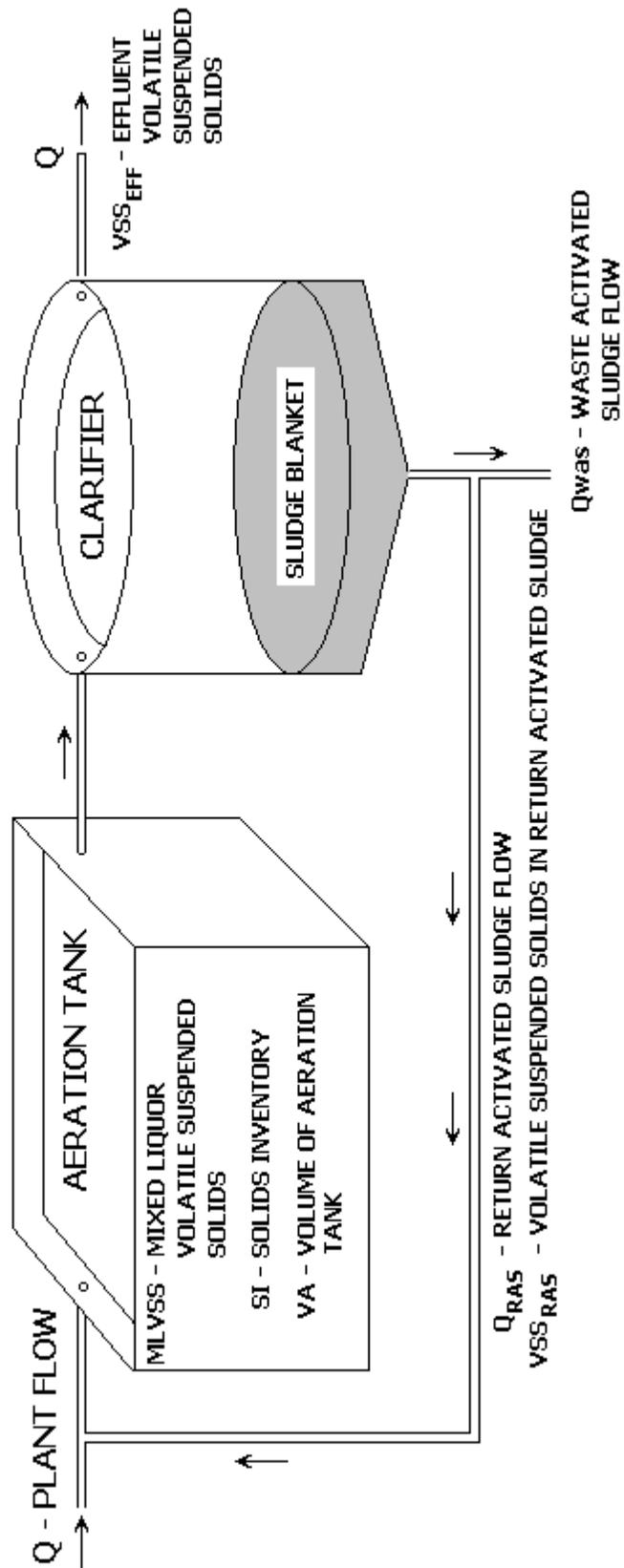


Figure 4.01

Process loading ranges for the activated sludge process are as follows:

| Process      | Aeration<br>(hrs.) | BOD<br>#/1000 cu.ft. | F/M       | Return<br>% |
|--------------|--------------------|----------------------|-----------|-------------|
| High         | 2-3                | 100                  | 1.0       | 100         |
| Conventional | 4-8                | 30-40                | 0.2-0.5   | 25-75       |
| Extended     | 18-30              | 10-20                | 0.01-0.15 | 50-100      |

Within these three loading ranges, the mixing regime and flow patterns can be varied (see Figure 4.02).

#### Mixing regime:

The complete mix activated sludge process was developed in 1927 to address high organic and/or toxic loads. In this system, the characteristics of the mixed liquor are similar throughout the aeration tank. From an operational point of view, tanks with detention time of 2 to 4 hours can be considered as complete mix. Since there is a low level of food available to a large mass, complete mix is able to handle large surges of organic loading.

Plug flow is defined as flow in which individual particles of feed pass through the reactor vessel in the same sequence they entered. Long, narrow tanks approach plug flow. This process was developed in 1917 at the Lawrence Experimental Station.

#### Flow variations:

In 1951, Ullrick & Smith developed the contact stabilization process. Contact stabilization uses a short-term contact tank and a sludge stabilization tank with about six times the detention time used in the contact tank.

Step feed is a modification of the plug flow configuration in which influent is fed at two or more points along the length of the aeration tank. This process was developed in New York City in the mid 1930s.

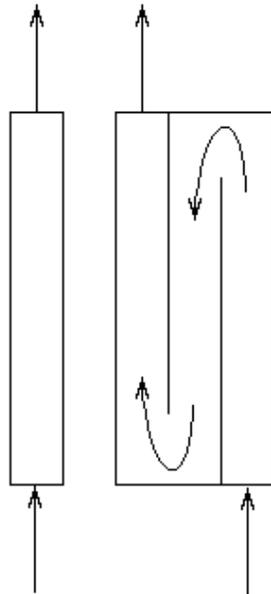
Step Aeration involves distributing the influent wastewater in a stepwise fashion from the influent to the effluent end.

Tapered Aeration involves distributing the air proportional according to the air demands from the influent to the effluent end.

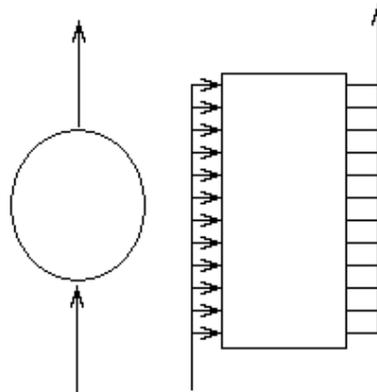
As a general rule, plug flow is used under the most lightly loaded conditions. Step feed is used as the organic or hydraulic load increases. Contact stabilization is used under peak hydraulic or organic load.

**MIXING REGIME**

**A. PLUG FLOW**

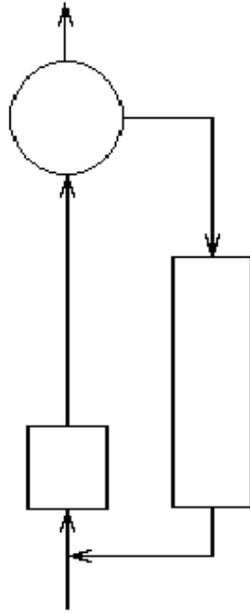


**B. COMPLETE MIX**



**FLOW VARIATIONS**

**A. CONTACT STABILIZATION**



**B. STEP FEED**

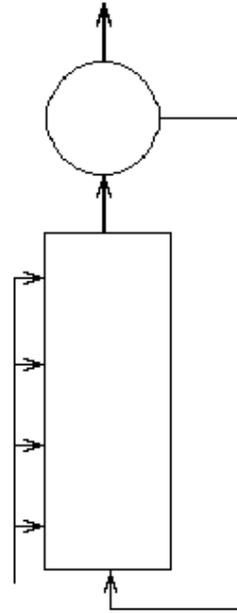


Figure 4.02

## V. SOLIDS ACCUMULATION

Solids will accumulate in activated sludge systems unless they are constantly wasted. This accumulation results from: 1) the removal of applied BOD, 2) the production of new cells through synthesis, and 3) the removal of inert materials. Offsetting this accumulation are: 1) the endogenous respiration of the new cells, 2) the loss of solids out the effluent, and 3) intentional wasting.

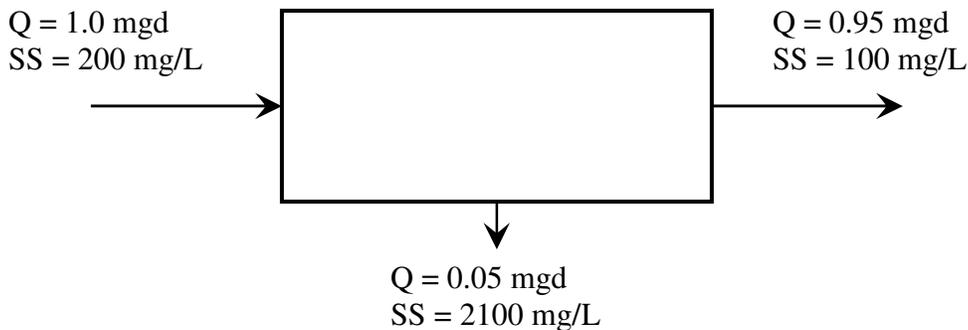
Mass balances can be used to mathematically define this accumulation. In words, the equation for mass balance is:

$$\text{accumulation} = \text{inflow} - \text{outflow} \pm \text{net growth}$$

$$\text{For solids mass, lbs/day} = (\text{flow, mgd})(\text{solids, mg/L})(8.34)$$

For primary clarifiers, the accumulation of solids is assumed to be zero or the sludge blanket will increase and the net growth is zero because there is no bio-conversion, therefore:

$$\text{inflow} = \text{outflow}$$



For an activated sludge system, the accumulation of biological solids can be expressed as:

$$\text{accumulation} = \text{inflow} - \text{outflow} + \text{net growth} - \text{endogenous decay}$$

$$= QX_o - QX + \frac{U_m X S}{K_s + S} - K_d X V$$

where,  $K_d$  = endogenous decay coefficient

$V$  = reactor volume

$Q$  = flow rate

$X_o$  = concentration of microorganisms, influent

$X$  = concentration of microorganisms in reactor

$U_m$  = maximum specific growth rate

$K_s$  = half velocity constant

$S$  = concentration of the growth-limiting substrate

Assuming steady state, accumulation = 0  
 Assuming negligible influent solid,  $X_0 = 0$

$$\frac{Q}{V} = \frac{U_m S}{K_S + S} - K_d$$

$$\frac{1}{\theta} = \frac{Q}{V}$$

Where  $\theta$  = hydraulic detention time

$$\theta_c = \frac{V_x}{Q_x} \quad \begin{array}{l} \text{mass of cells in reactor} \\ \text{mass of cells wasted} \end{array}$$

Where  $\theta_c$  = mean cell residence time

Substituting  $\theta_c$  for  $\theta$

$$1 = \frac{U_m S}{K_S + S} - K_d$$

$$\frac{1}{\theta} = \frac{Q}{V}$$

$$\text{Let } \frac{U_m S}{K_S + S} = Y(F/M)$$

$$\therefore \frac{1}{\theta_c} = Y(F/M) - K_d$$

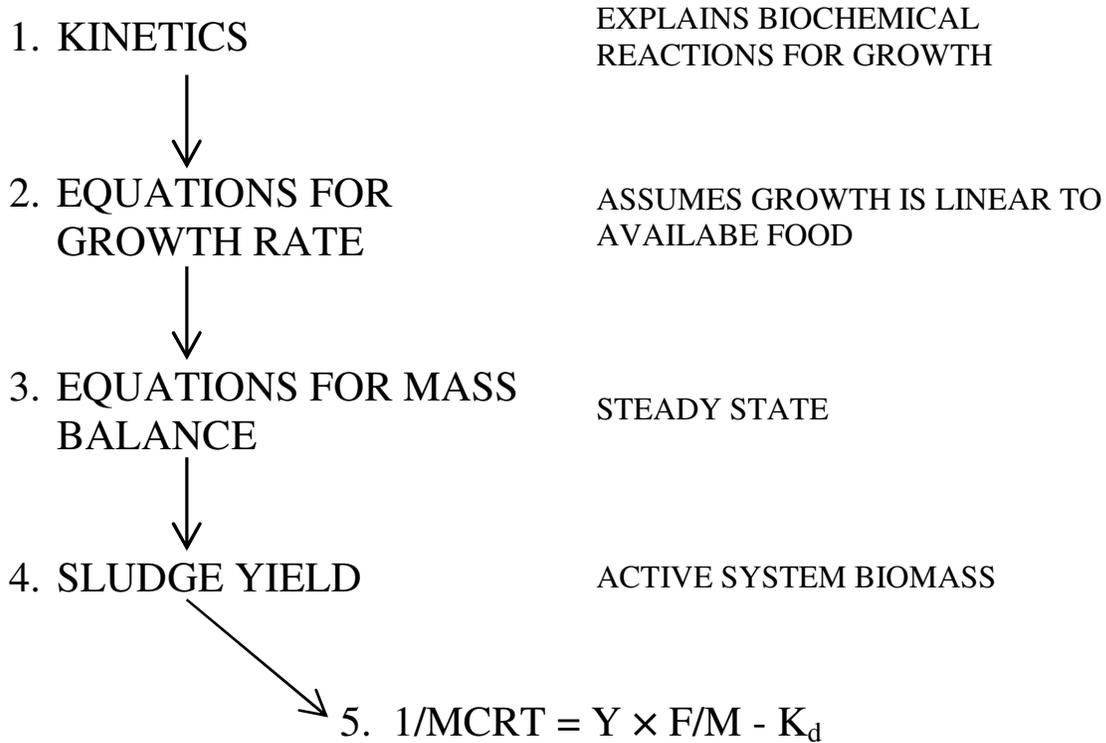
where,

$\theta_c$  = mean cell residence time  
 $Y$  = sludge yield coefficient  
 $F/M$  = food to mass ratio  
 $K_d$  = endogenous coefficient

See Figure 5.01 for a diagram of the derivation of F/M & MCRT relationship.

Note: Growth is related to loading (F/M) and the sludge age. Also control of the F/M ratio implies control of the sludge age (SRT) and vice versa.

# DERIVATION OF F/M & MCRT RELATIONSHIP



WHERE: MCRT = Mean Cell Residence Time  
Y = Sludge Yield Coefficient  
F/M = Food to Mass Ratio  
K<sub>d</sub> = Endogenous Coefficient

Figure 5.01

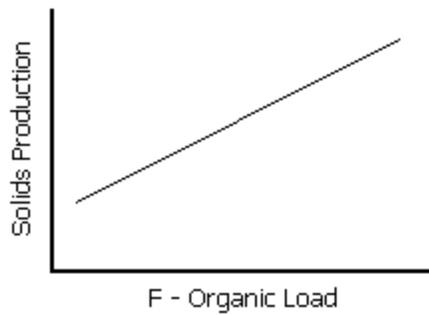


Figure 5.02

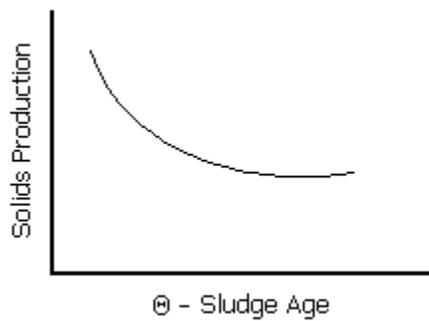


Figure 5.03

From the relationship above the net growth of biological solids per pound of organic loading can be given as:

| Process      | lb solids/lb BOD |
|--------------|------------------|
| High         | 0.50             |
| Conventional | 0.40 – 0.50      |
| Extended     | 0.15 – 0.30      |

In addition to the net growth of biological solids, activated sludge systems will accumulate inert solids from the non-biodegradable raw influent TSS. These inert solids are represented by the inert fraction of the incoming solids and the non-biodegradable solids (generally 40 percent of the volatile fraction).

Example: Calculate the total solids production (accumulation) in an extended aeration plant.

Given: TSS = 100 lbs/day  
VSS = 85 lbs/day  
BOD = 100 lbs/day

Solution: Accumulation = net growth + inert + non-biodegradable

Example: Calculate the total solids production (accumulation) in a high rate plant.

Given: TSS = 100 lbs/day  
VSS = 85 lbs/day  
BOD = 100 lbs/day

Solution: Accumulation = net growth + inert + non-biodegradable

$$= 0.2 \times (100 \text{ lbs/day BOD}) + \frac{100 - 85}{100} \times (100 \text{ lbs/day TSS}) + 0.4 \times \frac{85}{100} \times (100 \text{ lbs/day TSS})$$
$$= 69 \text{ lbs/day}$$

An example can be used to illustrate the concepts of sludge inventory, F/M SRT, and solids production.

Example: Calculate the F/M, SRT, and solids production.

Given: F = 100 lbs/d  
M = 300, 100, 1000  
Y = 0.55  
Kd = 0.02

Solution:

1a)  $F/M = 100/300 = 0.33$

1b)  $1/SRT = Y(F/M) - Kd$

$$SRT = 1/0.55(0.33) - 0.02$$

$$SRT = 6.2 \text{ days}$$

1c) solids accumulation =  $Y(F) - M(Kd)$   
 $= 0.55(100) - 300(0.02)$   
 $= 49 \text{ lbs}$

$$1d) \text{ SRT} = M/W$$

$$= 300/49$$

$$= 6.1 \text{ days}$$

$$2a) F/M = 100/100 = 1.0$$

$$2b) \text{ SRT} = 1/(0.55(1.0) - 0.02) = 1.9 \text{ days}$$

$$2c) \text{ solids accumulation} = 0.55(100) - 100(0.02) = 53 \text{ lbs}$$

$$2d) \text{ SRT} = M/W = 100/53 = 1.9 \text{ days}$$

$$3a) F/M = 100/1000 = 0.01$$

$$3b) \text{ SRT} = 1/(0.55(0.1) - 0.02) = 28.6 \text{ days}$$

$$3c) \text{ solids accumulation} = 0.55(100) - 1000(0.02) = 35 \text{ lbs}$$

$$3d) \text{ SRT} = M/W = 1000/35 = 28.6 \text{ days}$$

In this example, the aeration tank MLSS (M) at a given loading (F) is varied from 300, 100 to 1000 lbs. As shown, the F/M ratio varies from 0.33 (conventional), to 1.0 (high) and finally to 0.1 (extended). At these three loading rates, the net growth of biological solids (W) is 49 lbs., 53 lbs., and 35 lbs., respectively. This represents 0.49, 0.53 and 0.35 pounds of solids per pound of BOD.

## VI. COMPLETE MIX ACTIVATED SLUDGE EQUATIONS<sup>1</sup>

Developed by McKinney the following equations apply to a complete mix activated sludge systems in the declining growth phase.

The unmetabolized substrate in the effluent is calculated as follows:

$$F = \frac{F_i}{K_m t + 1} \quad 6.1$$

Where  $F$  = unmetabolized BOD in the effluent, mg/L  
 $F_i$  = influent BOD, mg/L  
 $K_m$  = metabolism factor, 7.2/hr at 20°C  
 $t$  = raw waste aeration time, hour

The value  $F$  represents only the unmetabolized substrate in the effluent and does not include excess microbial solids carryover.

Effluent BOD is computed from the following equation:

$$\text{BOD}_{\text{eff}} = F + K_b \text{Ma}_{\text{eff}} \quad 6.2$$

where  $\text{BOD}_{\text{eff}}$  = BOD in effluent, mg/L  
 $F$  = unmetabolized BOD from Equation 6-1  
 $K_b$  = 0.8 (BOD factor)  
 $\text{Ma}_{\text{eff}}$  = active microbial mass in the effluent, mg/L of VSS

The  $\text{Ma}_{\text{eff}}$  for Equation # can be calculated as follows:

$$\text{Ma}_{\text{eff}} = \text{Mt}_{\text{eff}} \times \frac{\text{Ma}}{\text{M}_T} \quad 6.3$$

Where  $\text{Mt}_{\text{eff}}$  = total suspended solids in effluent, mg/L  
 $\text{Ma}$  = active microbial mass, mg/L of VSS  
 $\text{M}_T$  = mixed liquor suspended solids, mg/L

Composition of the mixed liquor suspended solids in the aeration basin is determined by the following equation:

$$\text{M}_T = \text{Ma} + \text{Me} + \text{Mi} + \text{Mii} \quad 6.4$$

Where  $\text{M}_T$  = mixed liquor suspended solids, mg/L  
 $\text{Ma}$  = active microbial mass, mg/L of VSS  
 $\text{Me}$  = endogenous respiration mass, mg/L VSS

---

<sup>1</sup> John W. Clark, Warren Viessman Jr., Mark J Hammer, *Water Supply and Pollution Control*, IEP-A Dun-Donnelley Publisher, 1977

Mi = inert, nonbiodegradable organic suspended solids, mg/L  
 Mii = inert, inorganic suspended solids, mg/L of nonvolatile SS

Ma, Me, Mi, Mii are calculated as follows:

$$Ma = \frac{K_s F}{K_e - (1/t_s)} \quad 6.5$$

$$Me = 0.2 K_e M a_s \quad 6.6$$

$$Mi = M_{i_{inf}} t_s / t \quad 6.7$$

$$Mii = M_{ii_{inf}} t_s / t + 0.1(Ma + Me) \quad 6.8$$

where  $K_s$  = synthesis factor, 5.0/hr at 20°C

$K_e$  = endogenous respiration factor, 0.02/hr at 20°C

F = unmetabolized BOD

$t_s$  = sludge turnover time, hours

$t_s$  = lb of MLSS in aeration tank  
 lb of SS in effluent and waste sludge/day +/- lb of SS change in mixed liquor /day

$M_{i_{inf}}$  = nonbiodegradable organic suspended solids in influent, approximately 40% of the VSS in normal domestic wastewater, mg/L of VSS

$M_{ii_{inf}}$  = inert suspended solids in influent, mg/L of nonvolatile SS

t = raw waste aeration time, hour

The metabolism factor,  $K_m$ , synthesis factor,  $K_s$ , and endogenous respiration factor,  $K_e$ , are all temperature dependent. Values for these factors at temperatures other than 20°C may be determined using the following relationship:

$$K_T = K_{20}(1.072)^{T-20} \quad 6.9$$

where  $K_T$  =  $K_m$ ,  $K_s$ , or  $K_e$  at temperature T (°C)

$K_{20}$  =  $K_m$ ,  $K_s$ , or  $K_e$  at 20°C

The oxygen utilization rate of mixed liquor in the aeration tank is calculated by the following equation:

$$\frac{dO}{dt} = 1.5\left(\frac{F_i - F}{t}\right) - 1.42\left(\frac{Ma + Me}{t_s}\right) \quad 6.10$$

Where  $dO/dt$  = oxygen utilization rate, mg/l/hr  
 $F_i$  = influent BOD, mg/L

Figure 6.01 illustrates the relationship between the various solids makeup concentration versus sludge age.

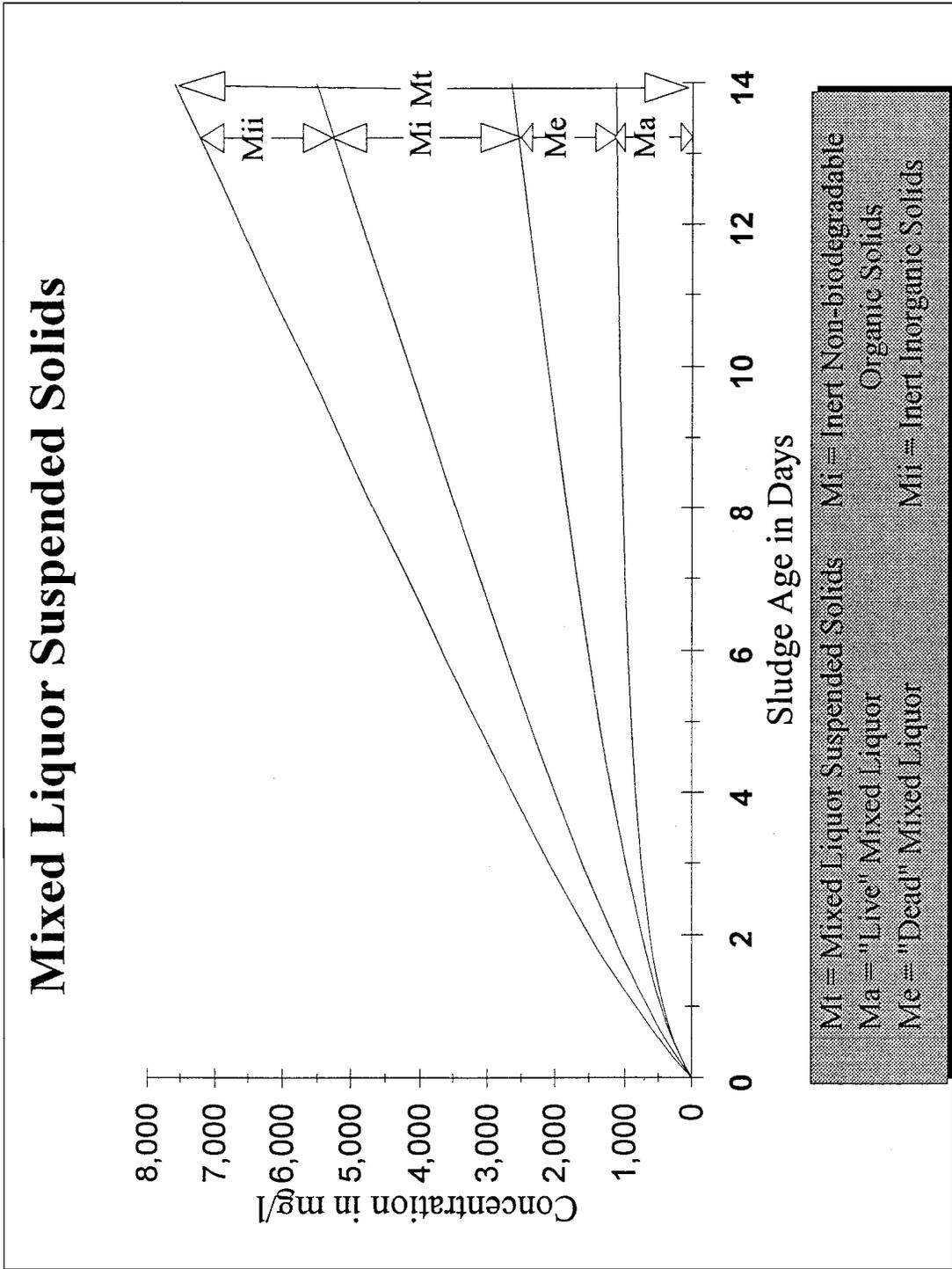


Figure 6.01

## VII. SOLIDS SEPARATION

Type I sedimentation is concerned with the removal of non-flocculent, discrete particles in dilute suspension. Under such conditions, the settling is called “unhindered” and is a function only of fluid properties and the characteristics of the particle. The settling of heavy inert matter, such as grit, is an example of this type of sedimentation.

Type II is applicable to dilute suspensions of flocculating particles, such as primary solids. In this case, heavier particles with large settling velocities overtake and coalesce with smaller particles to form still larger particles with increased rates of settling. The chance of particle contact increases with the depth of the settling tank. As a result, both overflow rate and the depth of the settling tank are important whereas Type I sedimentation depends on overflow rate only.

Zone Settling and Compression type of settling is characterized by activated sludge when the solids concentration exceeds approximately 500 mg/L. In such cases, the sludge settles at a uniform velocity initially which is a function of the initial solids concentration. Then a zone of transition occurs when the settling velocity decreases due to the increasing concentration of solids. Finally, a compression zone develops as the rising layer of settled sludge reaches the solid-liquid interface. Under these conditions, the particle is supported in part by the structure formed by the compacting mass.

In the separation of flocculent suspensions, both clarification of the liquid overflow and thickening of the sludge underflow are involved. The overflow rate for clarification should be such that the average rise velocity of the liquid overflowing the tank is less than the zone settling velocity of the suspension. The degree of thickening of the underflow to a desired concentration determines the tank surface area required and it is related to the solids loading to the unit. The thickening requirement is expressed in terms of mass loading (lb solids/ft<sup>2</sup>/day) or a unit area (ft<sup>2</sup>/lb solids/day).

$$\text{overflow rate} = \frac{Q}{\text{surface area, ft}^2} = \text{gpd/ft}^2$$

$$\text{solids loading} = \frac{(Q, \text{gpd} + Q_r, \text{gpd})(\text{MLSS, mg/L})(8.34)}{\text{surface area, ft}^2}$$

Note: The only controllable variable in the equation above is  $Q_r$ , return sludge flow.

| Type of Treatment                              | Overflow Rate<br>(gal/day/ft <sup>2</sup> ) |           | Solids Loading<br>(lb/ft <sup>2</sup> /day) |      | Depth<br>(ft) |
|--|---|-----------|---|------|---------------|
|  | Average                                     | Peak      | Average                                     | Peak |               |
| Primary followed by secondary                  | 800-1200                                    | 2000-3000 |   |      | 10-12         |
| Primary with WAS                               | 600-800                                     | 1200-1500 |   |      | 12-15         |
| Activated Sludge<br>(except extended aeration) | 400-800                                     | 1000-2000 | 20-30                                       | 50   | 12-15         |
| Extended Aeration                              | 200-400                                     | 800       | 5-25  | 40   | 12-15         |
| Pure Oxygen                                    | 400-800                                     | 1000-2000 | 25-35                                       | 50   | 12-15         |

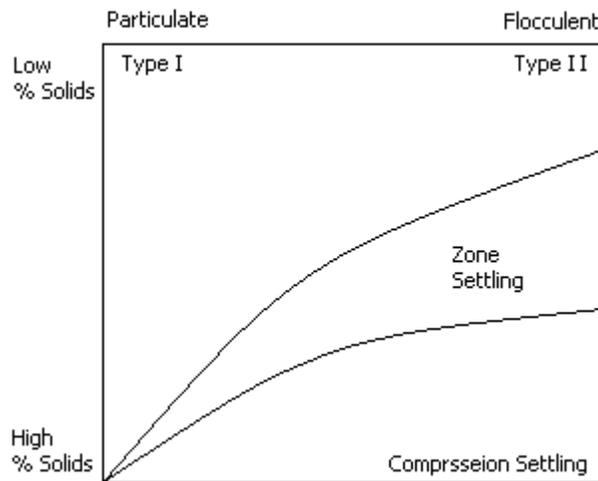


Figure 7.01

## ZONE SETTLING RATE

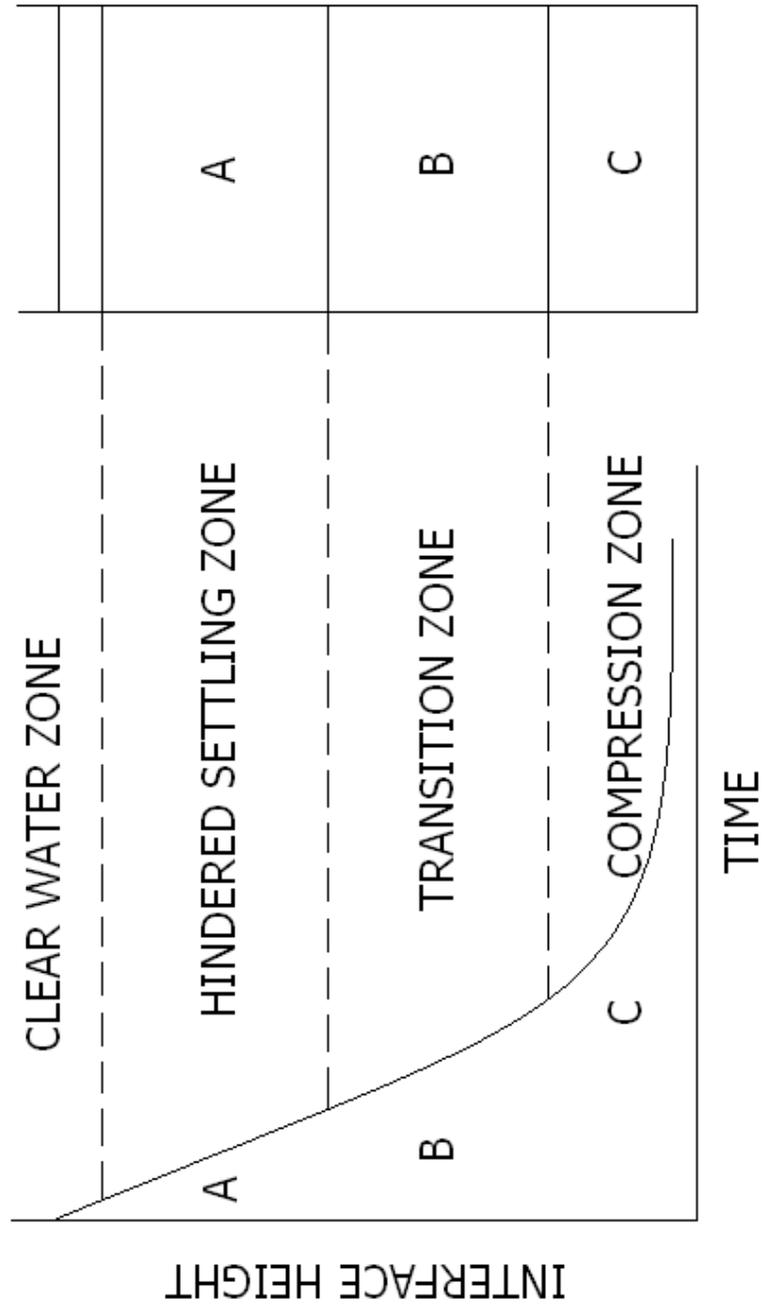


Figure 7.02

## VIII. SOLIDS FLUX THEORY<sup>2</sup>

Secondary clarifiers have three primary functions: clarification, thickening and storage. In general, the clarification function is satisfied as long as the thickening function is fulfilled. This generalization does not hold true if the mixed liquor is experiencing deflocculation, dispersed growth and pin floc. These conditions are the result of environmental factors in the aeration basin and usually cannot be corrected in the clarifier. Given this situation, the primary goal of secondary clarifier operation should be to satisfy the thickening function. The solids flux analysis is the best tool for evaluating settling characteristics which affect thickening.

Both gravity settling and bulk flow (recycle flow) carry solids to the bottom of an activated sludge clarifier. Figure 8.01 below shows the important aspects of solids flux theory.

Equation 8.1 indicates that the flux resulting from gravitational settling ( $G_s$ ) is a function of the solids concentration ( $C_i$ ) and the settling velocity ( $v_i$ ).

$$G_s = C_i v_i \qquad 8.1$$

---

<sup>2</sup> Datastream System Incorporated, *Performance Pac Manual*, 1990

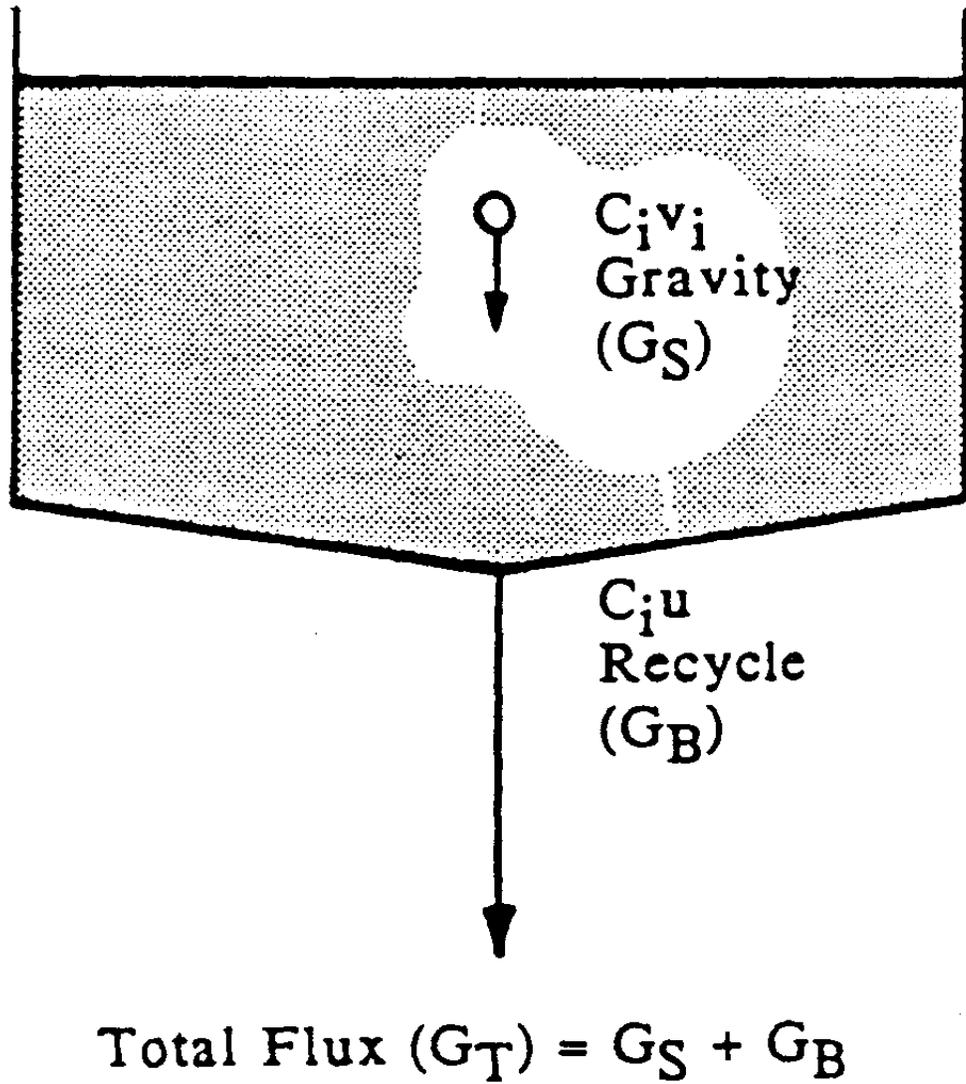


Figure 8.01

The settling velocity is dependent on the following factors:

- solids concentration
- temperature
- system organic loading
- aeration basin DO

It is important to evaluate the settling characteristics of the sludge frequently because of the effects of these variables. The accumulation of historical data provides a useful tool for predicting clarification problems.

As shown in equation 8.2 the bulk flux ( $G_B$ ) is dependent on the solids concentration and the bulk downward velocity ( $u$ ) imposed by the recycle.

$$G_B = C_i u \quad 8.2$$

The bulk velocity is a function only of recycle flow rate and, therefore, is a controllable process variable.

The total flux, as represented in equation 8.3, is the sum of the bulk and settling fluxes.

$$G_T = G_S + G_B = C_i(v_i + u) \quad 8.3$$

As the sludge thickens from the MLSS concentration to that of the underflow, it passes through all intervening concentrations. One of these concentrations is critical to clarifier operation and defines the solids handling capacity or limiting flux,  $GL$ . Equation 8.4 defines the applied flux  $G_A$  which represents the biosolids sent to the clarifier.

$$G_A = C_o(Q_I + Q_R)/CSA \quad 8.4$$

where:  $C_o$  = aeration basin MLSS concentration  
 $Q_I$  = influent flow rate  
 $Q_R$  = clarifier recycle flow rate  
 $CSA$  = clarifier surface area

The sludge blanket rises when the applied flux ( $G_A$ ) exceeds the solids handling capacity. If the condition persists, the solids blanket can rise and solids will be discharged out the effluent.

The previous equations do not consider the wastage flow rate as contributing to bulk flow. The more limiting condition occurs when wastage is not additive to recycle. Wastage is usually a small part of the clarifier sludge removal rate. In highly concentrated waste streams wastage should be considered. For this condition, the bulk downward velocity results from the sum of recycle rate and wastage rate.

$$G_B = C_i(u + w)$$

8.5

where: wastage flow rate ( $w$ ) is the continuous rate of sludge wastage

The state point method is one of the most useful techniques for evaluating the solids handling capacity of secondary clarifiers. This method uses a curve representing the gravitational settling characteristics and two operating lines to define feasible operating conditions.

The two operating lines constitute a graphical material balance on solids constrained by the settling characteristics defined by the flux curve. The Y axis of the graph represents the gravitational flux in lbs/sq.ft.-day. The X axis represents the MLSS concentration in mg/L. A sample curve is shown in Figure 8.02.

The overflow line begins at the origin and has a slope equal to the plant influent flow rate ( $Q_i$ ) divided by the clarifier surface area (CSA) on line. The slope is expressed in feet per day. The overflow rate is the influent flow rate minus the wastage rate divided by the clarifier surface area on line. Since the wastage rate is generally small in comparison to the influent flow, the approximation does not cause an appreciable error.

The intersection of overflow rate operating line and a vertical line drawn from the aeration basin MLSS concentration is known as the state point. The state point acts as a pivot point for the second operating line. The second line represents recycle flow rate from the clarifier to the aeration basin. The slope of the recycle flow rate operating line is equal to the negative of the recycle rate ( $Q_R$ ) divided by the clarifier surface area on line, or the negative of the bulk velocity ( $-u$ ). The intersection of the recycle rate operating line with the X axis represents the predicted clarifier underflow MLSS concentration.

The clarifier is under loaded and operates successfully when the shaded area confined by the two operating lines is completely below the flux curve. The clarifier is overloaded and solids will be transferred from the aeration basin to the clarifier if a portion of the shaded area lies above the flux curve. The sludge blanket will rise and the applied flux, which is directly related to the MLSS concentration, will decrease. After the applied flux decreases the system will stabilize with a lower MLSS and a higher sludge blanket.

Operational changes are readily seen by the state point approach. The variation in influent flow rate is illustrated in Figure 8.03. As the flow rate increases from  $Q_{11}$  to  $Q_{12}$ , the recycle flow operating line moves upward and becomes critically loaded. An applied flux greater than these results in the transfer of solids from the aeration tank to the secondary clarifier. As the flow increases to  $Q_{13}$  the recycle operating line moves above the flux curve which results in an overloaded clarifier.

The effects of recycle rate changes are illustrated by Figure 8.04.  $Q_{r1}$  depicts the underloaded condition while  $Q_{r2}$  depicts a critically loaded condition and  $Q_{r3}$  depicts an

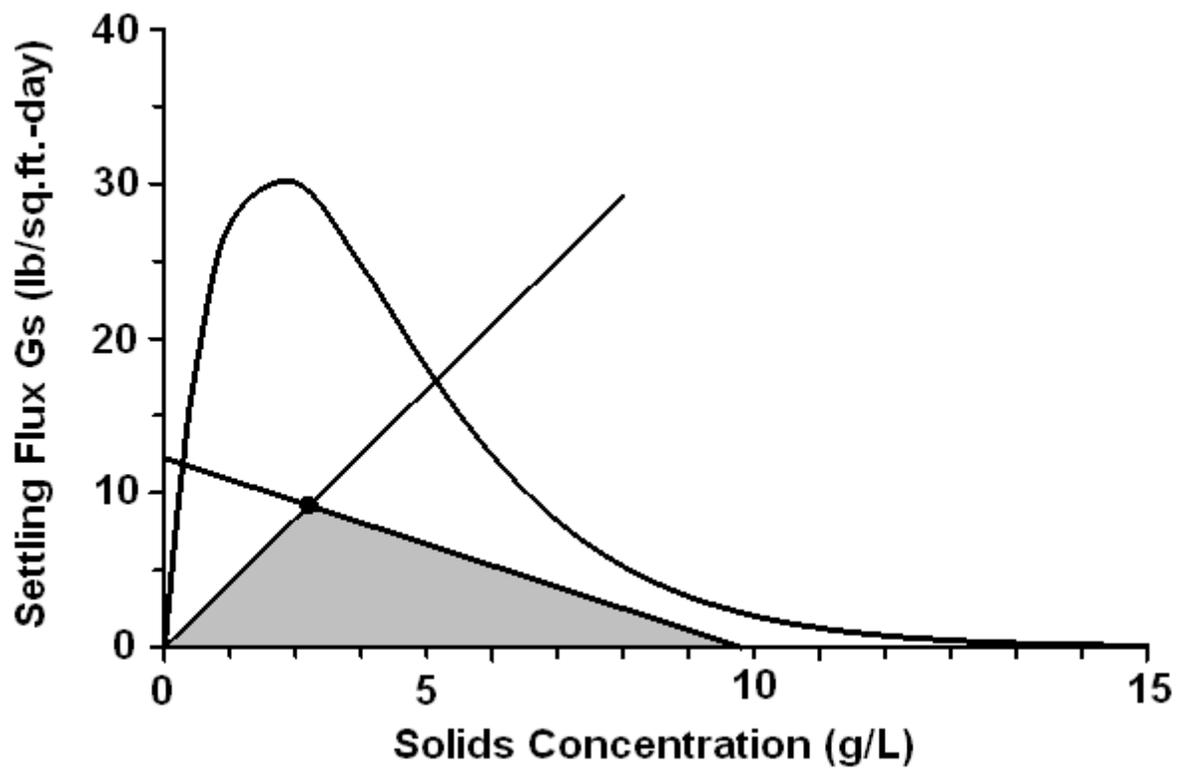


Figure 8.02

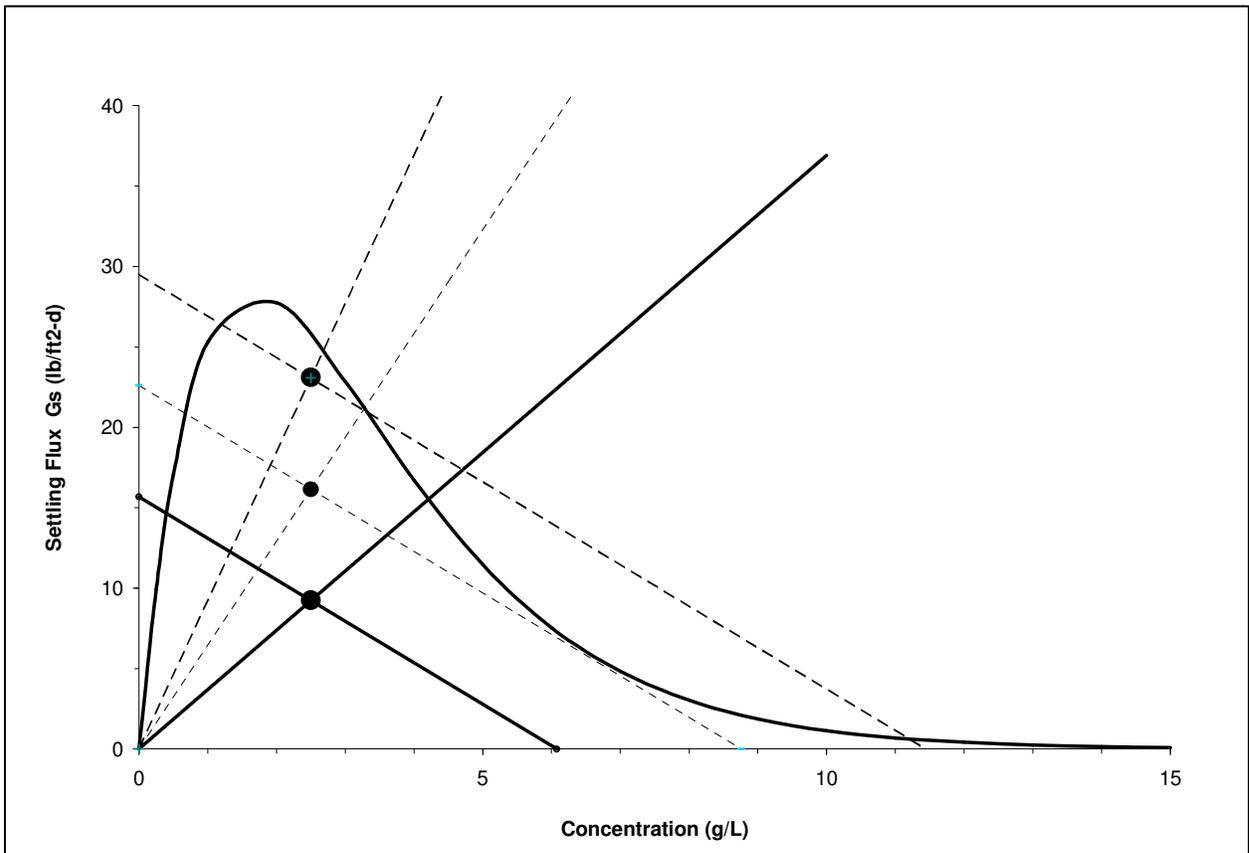


Figure 8.03

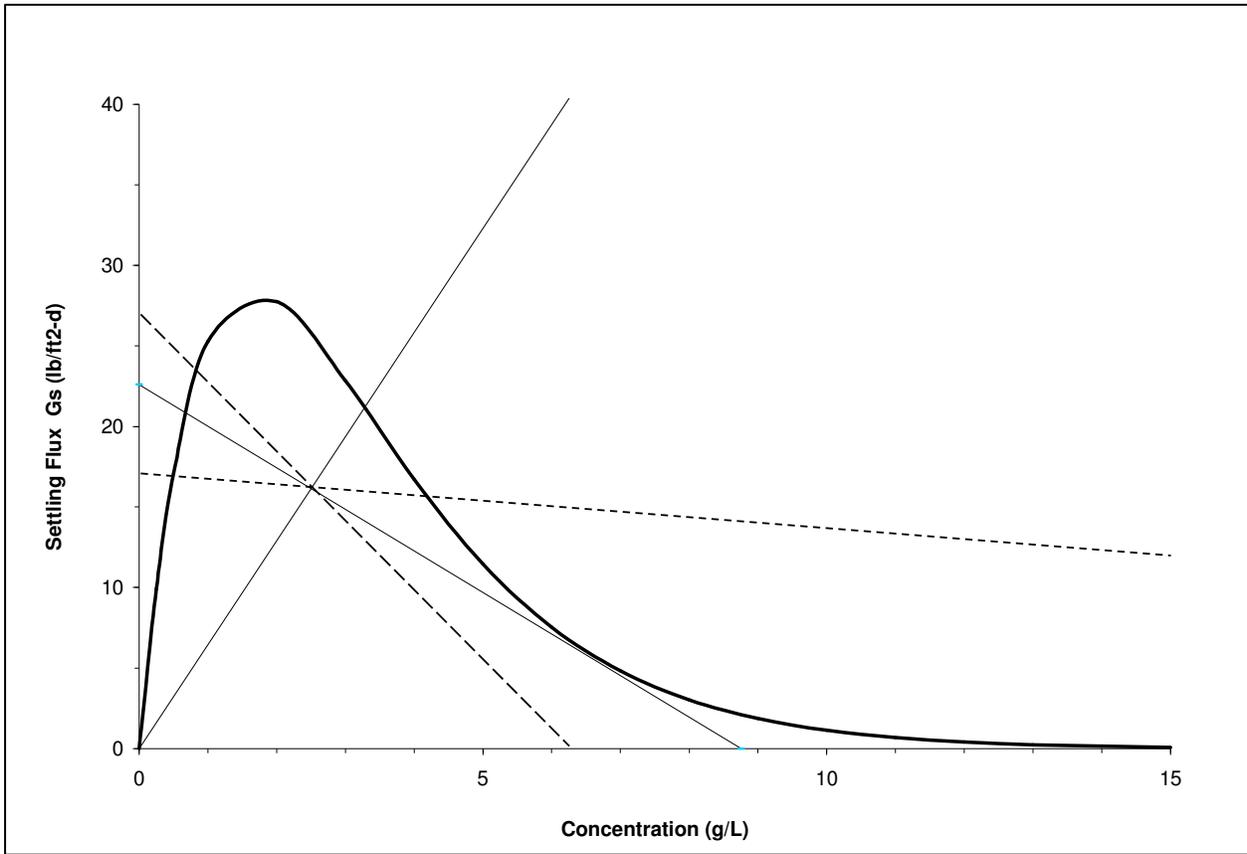


Figure 8.04

overloaded condition. Decreasing the recycle flow rate increases the underflow concentration and lowers the pumping costs. However, these benefits cause lower limiting flux thereby less solids handling capacity. Optimizing the performance means selecting the lowest recycle rate with an acceptable margin of safety.

An increase in organic loading generally means an increase in the MLSS concentration. The state point analysis can be used to evaluate an increase in the MLSS concentration. As shown in Figure 8.05 the clarifier goes from an underloaded condition to an overloaded condition as the MLSS increases. As illustrated the overflow rate line remains unchanged because the influent flow rate remains the same. Also, the recycle rate does not change therefore the slope on the recycle operating line remains constant. However the position of the recycle operating line changes because as the MLSS increases the state point moves upward.

Many changes can occur that results in deterioration of the sludge settling characteristics (see Figure 8.06). This deterioration results in changes in the shape and position of the gravity flux curve. As a result of these changes a clarifier can go from an underloaded to an overloaded condition at constant MLSS, influent flow and recycle flow (see Figure 8.06).

## IX. MASS BALANCE

Where is the Sludge?  
 How long has it been there?  
 How much sludge is there?

### Sludge Units Definition

#### Pounds

Concentration X Volume in MG X 8.34  
 (concentration in mg/L)

#### Aerator Sludge Inventory (ASI)

ASI, lb = MLSS, mg/L X Volume, MG X 8.34 9.1

#### Clarifier Sludge Inventory (CSI)

CSI, lb = CSC, mg/L X Volume, MG x 8.34 9.2

#### Total Sludge Inventory (TSI)

TSI, lb = ASI, lb + CSI, lb 9.3

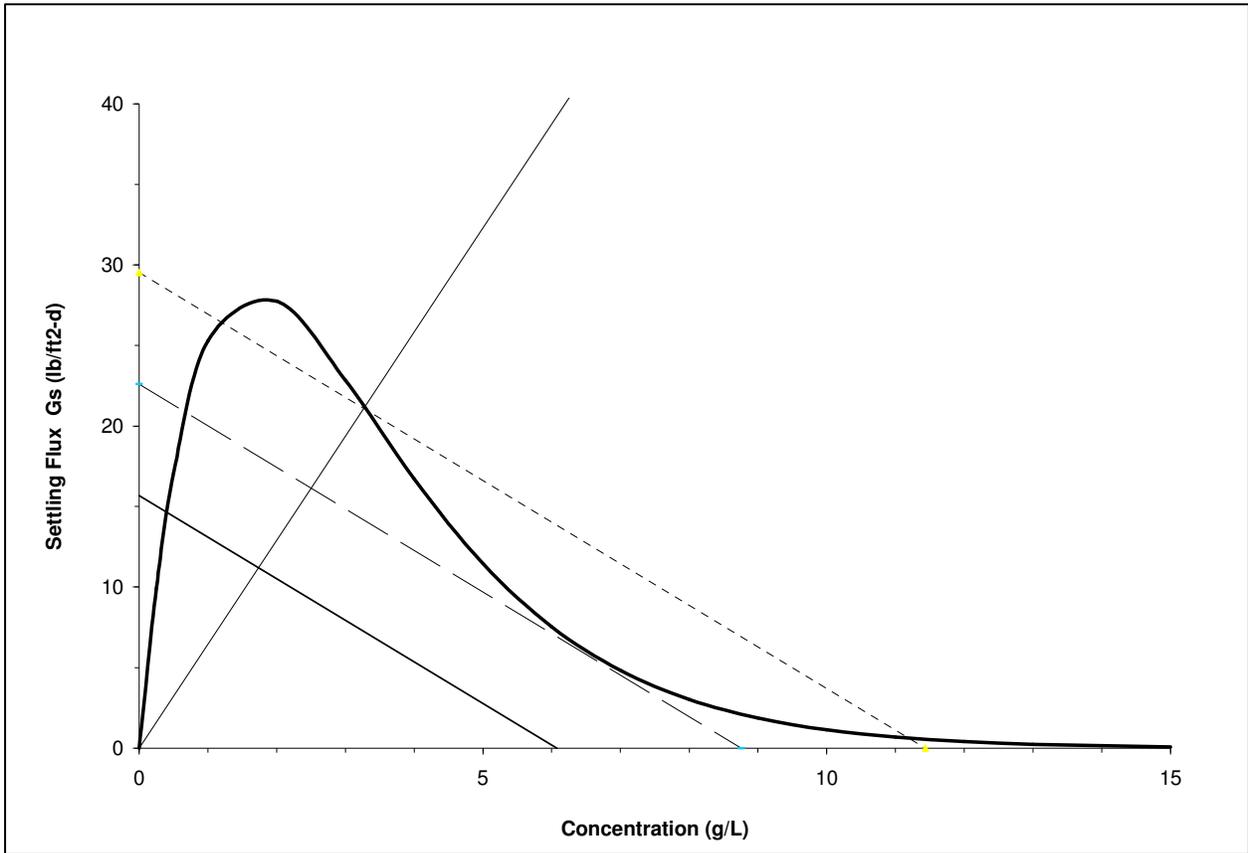


Figure 8.05

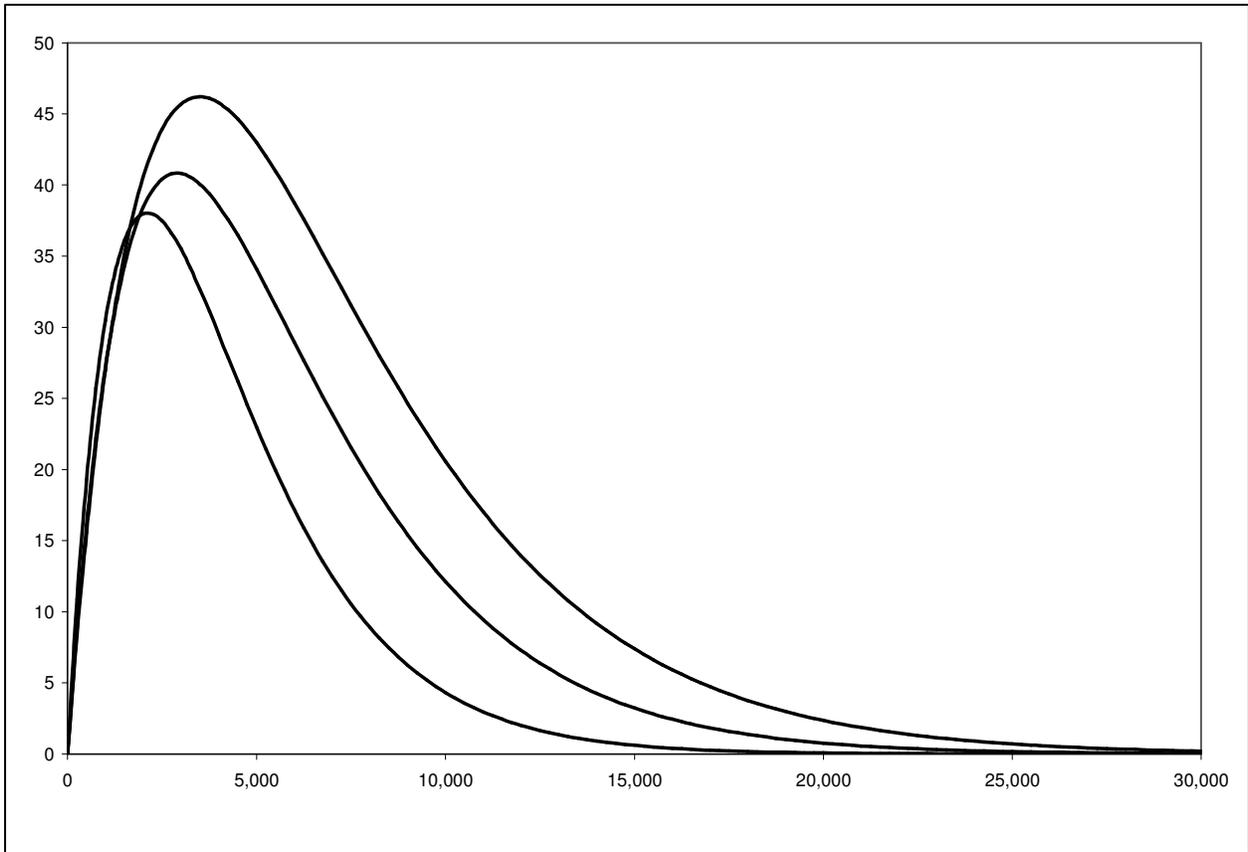


Figure 8.06

Return Activated Sludge (RAS)

$$\text{RAS, lb/day} = \text{RASSS, mg/L} \times \text{RSF, MG} \times 8.34 \quad 9.4$$

Waste Activated Sludge (WAS)

Sludge Wasted from the system.

$$\text{WAS, lb/day} = \text{WSC, mg/L} \times \text{WSF, MGD} \times 8.34 \quad 9.5$$

Effluent Solids Lost (ESL)

Sludge lost in the effluent

$$\text{ESL, lb/day} = \text{TSS, mg/L} \times \text{Q, MGD} \times 8.34 \quad 9.6$$

Solids Inventory Lost (SIL)

Intentionally wasted sludge = WAS

Effluent Solids Lost = ESL

Sludge Inventory Lost

$$\text{SIL, lb/day} = \text{WAS, lb/day} + \text{ESL, lb/day} \quad 9.7$$

$$\text{SIL, lb/day} = (\text{WSC, mg/L} \times \text{WSF, MGD} \times 8.34) + (\text{Q, MGD} \times \text{TSS, mg/L} \times 8.34)$$

Mean Cell Residence Time (MCRT)

$$\text{MCRT, days} = \frac{\text{TSI, lb}}{\text{WAS, lb/day} + \text{ESL, lb/day}} \quad 9.8$$

Clarifier Solids Detention Time (SDT<sub>c</sub>)

$$\text{SDT}_c, \text{ hours} = \frac{\text{CSI} \times 24}{\text{RAS, lb/day}} \quad 9.9$$

RSF and WSF are measured separately from the same draw-off point in the clarifier.

$$\text{SDT}_c, \text{ hours} = \frac{\text{CSI, lb} \times 24}{(\text{RSF} + \text{WSF}), \text{ MGD} \times \text{RASSS, mg/L} \times 8.34} \quad 9.10$$

RSF and WSF are measured from separate draw-off points in the clarifier

$$\text{SDTc, hours} = \frac{\text{CSI, lb X 24}}{(\text{RAS} + \text{WAS}), \text{ lb/day}} \quad 9.11$$

Aeration Solids Detention Time (SDTa)

$$\text{SDTa, hours} = \frac{\text{ASI, lbs X 24}}{(\text{Q} + \text{RSF}), \text{ MGD X MLSS, mg/L X 8.34}} \quad 9.12$$

Oxidation Pressure

$$\text{OXp} = \text{MLSS, mg/L X SDTa} \quad 9.13$$

## X. NITRIFICATION

Nitrogen in the Environment

- atmosphere
- the Earth's crust
- hydrosphere
- tissues of living and dead organisms

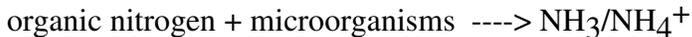
Nitrogen compounds

| Compound     | Formula                      | Oxidation State |
|--------------|------------------------------|-----------------|
| Ammonia      | NH <sub>3</sub>              | -3              |
| Ammonium ion | NH <sub>4</sub> <sup>+</sup> | -3              |
| Nitrogen gas | N <sub>2</sub>               | 0               |
| Nitrite ion  | NO <sub>2</sub> <sup>-</sup> | +3              |
| Nitrate ion  | NO <sub>3</sub> <sup>-</sup> | +5              |

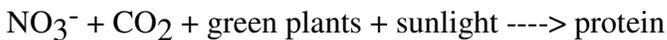
Fixation: Fixation of nitrogen means the incorporation of inert gaseous nitrogen into a chemical compound such that it can be used by plants and animals.

N<sub>2</sub> ----> biological ----> organic nitrogen  
 ----> lightning ----> nitrate  
 ----> industrial ----> ammonium, nitrate

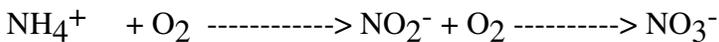
Ammonification: Ammonification is the change from organic nitrogen to the ammonium form. An important hydrolysis reaction involves urea. In general, ammonification occurs during decomposition of animal and plant tissue.



Synthesis: Synthesis is a biochemical mechanism that used ammonium or nitrate compounds to form plant protein and other nitrogen-containing compounds.



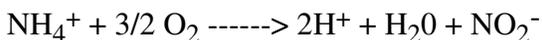
Nitrification: Nitrification is the biological oxidation of ammonium. This is done in two steps, first to the nitrite form, then to the nitrate form. Two specific chemoautotrophic bacterial genera are involved, using inorganic carbon as their source of cellular carbon.



ammonium      *Nitrosomonas*      nitrate      *Nitrobacter*      nitrite

Nitrogen is most often found in wastewater as ammonia and organic nitrogen in the form of amines and other nitrogenated compounds. During the wastewater treatment process, organic nitrogen is converted to ammonia by ammonifying bacteria. Ammonia is removed in activated sludge processes by 1) stripping to the atmosphere (this can be significant at pH above 8), 2) assimilation into bacteria cells, and 3) bacterial nitrification (which may be followed by denitrification). Nitrification is a naturally occurring, two-step aerobic biological process in which autotrophic bacteria oxidize the ammonium ion to nitrite or nitrate. In the first step, the ammonia is oxidized to nitrite by *Nitrosomonas* bacteria.

Step 1:

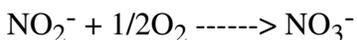


Oxygen Required = 3.43 lb/lb N oxidized

Alkalinity Required = 7.14 lb/lb N oxidized

Step 2:

Next, the nitrite is oxidized to nitrate by *Nitrobacter* bacteria.



For both reactions together:

Total oxygen requirement = 4.57 lbs/lb N oxidized

Total alkalinity requirement = 7.14 as CaCO<sub>3</sub>/lb N oxidized

From the reactions above it can be seen that oxidation of ammonia to nitrite produces acid. Once released by the bacteria, the acid reacts immediately with different forms of alkalinity. This tends to decrease the pH of the mixed liquor.

The nitrification process requires a significant amount of oxygen, produces a small amount of biomass, and results in substantial destruction of alkalinity through the production of hydrogen ions

The factors that influence nitrification include: influent characteristics, dissolved oxygen, BOD loading, detention time, pH/alkalinity, temperature, mass of nitrifying bacteria, and a lack of toxins. Nitrification consumes a large amount of oxygen. In order for uninhibited nitrification to occur, an operating D.O. level of 2.0 mg/L is suggested. Nitrifying bacteria do not compete well against heterotrophic bacteria for D.O. and nutrients. Therefore, before nitrification can take place, the soluble BOD must be sufficiently reduced to eliminate this competition, generally down to 20-30 mg/L. This condition is usually achieved in activated sludge systems. In general, the longer the detention time, the more likely that nitrification will occur. Activated sludge plants are able to nitrify in 6 - 48 hours. Nitrification is enhanced at higher pH's where 7.5 - 8.5, although nitrifying bacteria can adapt outside this range. Nitrification tends to produce acids and alkalinity is consumed at a rate of 7.14 lbs CaCO<sub>3</sub>/lb NH<sub>3</sub> oxidized. Therefore, sufficient alkalinity must be present to buffer the acids produced during nitrification. Alkalinity concentrations less than 150 mg/L inhibit both nitrification. The rate of nitrification is greatly influenced by temperature. As the temperature increases, the rate of nitrification increases. Temperatures greater than 20 degrees up to about 35 degrees C enhance nitrification. Nitrification slows down dramatically or may stop altogether at around 5 degrees C. In the winter activated sludge plants get down to 0 degrees C. *Nitrobacter* is more temperature sensitive than *Nitrosomonas*. With decreasing temperature, *Nitrobacter* growth decreases resulting in decreased nitrification and a build-up of NO<sub>2</sub><sup>-</sup>.

A very important factor is that a sufficient population of nitrifying bacteria must be present in order to complete nitrification. These bacteria are attached growth organisms, meaning that they must attach themselves to the surface of an object. In an activated sludge plant, the surface is a floc particle. In a trickling filter or RBC, the surface is the artificial media. In lagoons and ponds, it is believed that nitrifiers may attach to sideslopes, baffles and algal particles.

Nitrifying bacteria are more sensitive to inhibitory compounds, such as heavy metals, than are the BOD reducing bacteria, thus the nitrifying bacteria would be the first ones to die off. Nitrifying bacteria are found in the soil and enter the waste treatment system

through infiltration and inflow. During the winter, when the ground is frozen, less nitrifying bacteria will be coming into the system.

Should any of the factors necessary for complete nitrification be missing or in limited supply, the nitrification cycle may not go to completion during the time the wastewater is contained in the treatment process. This phenomenon, called "partial nitrification", leaves ammonia and/or residual nitrite in the effluent. The residual ammonia and nitrite will exert an oxygen demand during the "standard" BOD test when sufficient numbers of nitrifying bacteria are present in the test sample.

Nitrifiers grow slowly compared to most other bacterial populations and therefore must be retained in the treatment process for a relatively long period of time. The nitrifying bacteria are mixed together with all other mixed liquor suspended solids. Therefore, their total retention time in the treatment process is the same as that for the rest of the activated sludge. The variable describing the total retention time of nitrifiers in the treatment process is the mean cell residence time (MCRT).

$$\text{MCRT} = \frac{\text{Mass of MLSS in the System}}{\text{Mass of WAS} + \text{Mass of Eff. TSS}}$$

In treatment processes that include unaerated reactors in addition to aerated reactors, it is useful to compute the specific amount of time that nitrifiers spend in the aerated reactors. This is termed the oxic SRT. The equation for computing oxic SRT is:

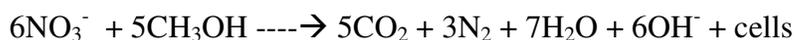
$$\text{OXIC SRT} = \frac{\text{Mass of MLSS under aeration}}{\text{Mass of WAS} + \text{Mass of Eff. TSS}}$$

The appropriate oxic SRT for a treatment process depends on how fast the nitrifiers can grow under the environmental conditions of the process. As discussed already, important environmental conditions include dissolved oxygen concentration, pH, and temperature. (See appendix Q for SRT calculations)

The conditions which promote nitrification in activated sludge treatment systems are:

1. Low BOD loading;
2. Adequate D.O. (1.0 – 2.0 mg/L);
3. Optimum pH (6.0 – 7.5);
4. Adequate temperature (5° – 45° C);
5. Long solids retention time (2 days or more); and,
6. Adequate MLVSS (1500 mg/L)

Denitrification is the biological reduction of nitrate to nitrogen gas. A fairly broad range of heterotrophic bacteria are involved in the process, requiring an organic carbon source for energy.



Alkalinity produced = 3.57 lbs as  $\text{CaCO}_3$  per lb nitrate denitrified  
Oxygen recovered = 2.86 lb per lb nitrate denitrified

For denitrification to occur, specific environmental conditions must be met. Most of the varieties of bacteria which can denitrify are facultative. However, if they have a choice they will get their energy from aerobic respiration because they get more energy with less effort. Therefore, anoxic (oxygen absent, nitrate present) conditions must be created for denitrification to occur. A small amount of denitrification can occur with DO present if the centers of the floc particles become anoxic.

The second critical factor for the reaction to occur is a source of carbon. A common carbon source is methanol. Some systems are designed to use raw influent.

Denitrification rates also increase and occur at low MCRT's as the water temperature increases. The optimum pH for denitrification is 7 to 8.

Nitrogen gas is relatively insoluble in water and forms small bubbles when produced in the denitrification process. These bubbles can attach to floc particles and float them to the surface. Denitrification in a clarifier can increase effluent turbidity and cause significant accumulation of scum and floating sludge on the surface.

In wastewater treatment the cycling of nitrogen is very important. The control of the activated sludge process is important in this cycling. Figure 10.01 depicts the cycle through which nitrogen travels in the wastewater treatment process.

The control strategies for nitrification/denitrification are not always successful and may result in further complications. First, you must identify whether nitrification/denitrification is required. The most common control strategies if nitrification/denitrification is not required are:

1. Increase recycle rate. This does keep the sludge off the bottom of the clarifier and limits denitrification. Unfortunately a thin sludge may result, and the floc is susceptible to damage by mechanical aerators.
2. Increase wasting rate. An increase wasting rate does reduce the SRT and thus reduce nitrification. Unfortunately, a poor settling sludge may result.
3. Limit the dissolved oxygen. Nitrification is an aerobic process which requires a lot of oxygen (4.6 lbs of oxygen per lb. of ammonia nitrogen converted). Limiting the oxygen does not promote the microbes that are also required for carbonaceous BOD removal.

The proper monitoring of an activated sludge system is essential to the troubleshooting process. A simple and inexpensive method for monitoring nitrification and denitrification is alkalinity. Theoretically 7.14 mg of alkalinity is destroyed per mg of  $\text{NH}_3\text{-N}$  oxidized. Denitrification produces 3.57 mg of alkalinity per mg of nitrate

# Wastewater Nitrogen Cycle

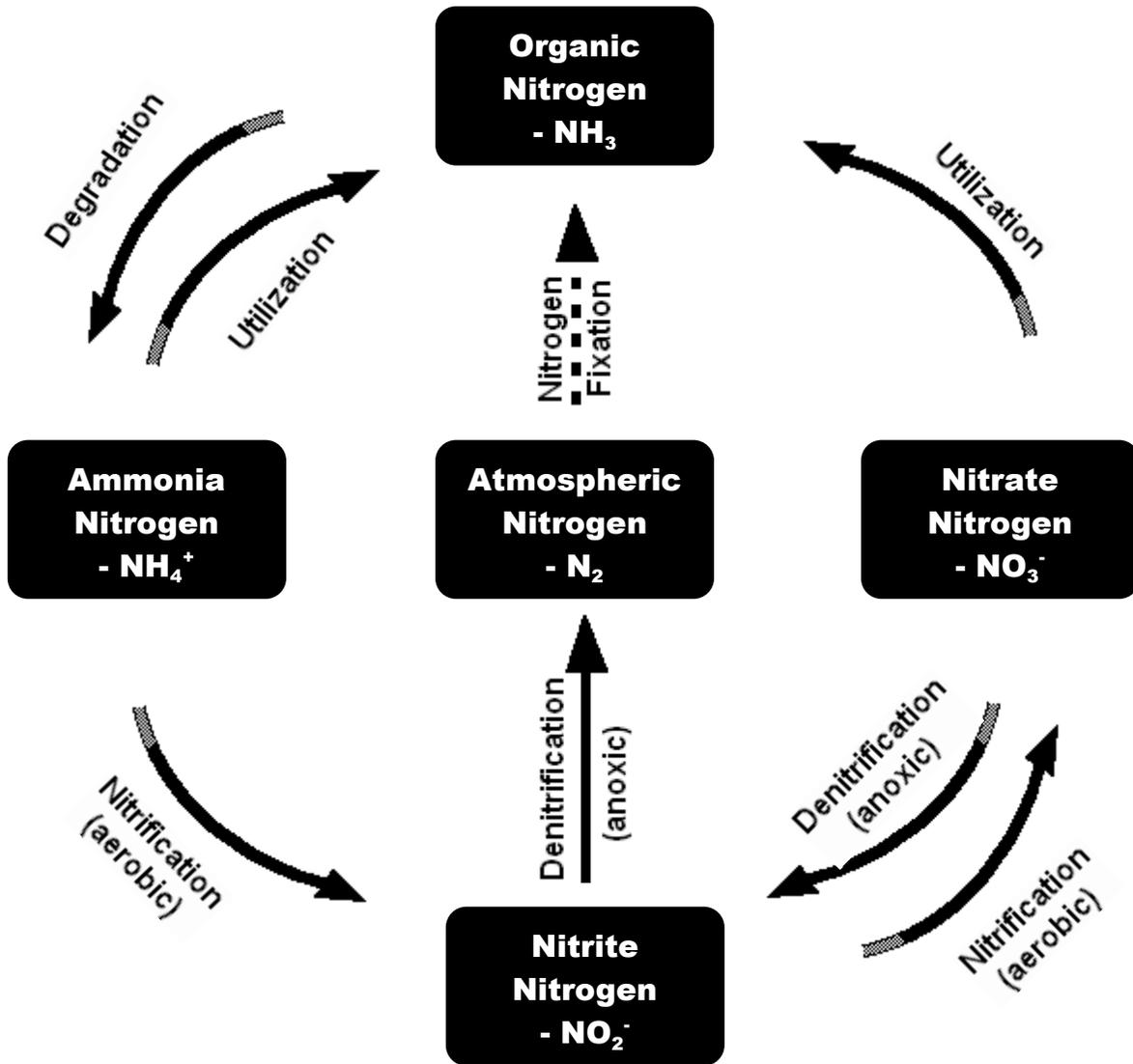


Figure 10.01

converted to  $N_2$ . Thus, by monitoring the changes in alkalinity in the influent and effluent of the aeration basin, it is possible to estimate the extent of nitrification. Monitoring the pH of the aeration basin and comparing  $BOD_5$  results with and without nitrifying inhibitors can also be used to determine the nitrifying state of the system.

The oxidation-reduction-potential (ORP) relates to measuring the effects of growth. The ORP uses a pH meter with either a specific ORP probe or a combination pH/ORP probe. The millivolt scale on the meter indicates ORP. The ORP measures the relative amount of oxidized versus reduced materials in the system (or capability of the sludge to gain or release electrons). For instance oxygen or  $O_2$  represents the upper end of the oxidation scale and moves the ORP into the positive or plus range. A positive ORP shows the system has potential to gain electrons, but nitrate is also an oxidized form of nitrogen and adds to the positive value. Thus, if there is nitrate and dissolved oxygen available, the ORP should be positive and large, probably 200-400 mV. Any nitrogen as ammonia will cause that value to be lower. Any anaerobic conditions will make the value lower yet. A negative ORP shows the system has electrons to release and contains little dissolved oxygen or nitrate.

In 1992, Goronszy and his coworkers developed a chart relating the ORP to various biological processes. Appendix K shows eight different biological growth activities and the range of ORP within which that activity occurs. For instance oxidation of organic carbon proceeds when the ORP is between approximately +50 and +225 mV while nitrification may occur between +100 and +325 mV. If anoxic conditions prevail, the ORP would range from about -50 and +50 mV. Thus, by periodic readings of the ORP at the end of the aeration tank and at the clarifier weirs, an operator can tell the amount of nitrification and denitrification in the aeration tank and clarifier.<sup>3</sup>

## XI. PROCESS CONTROL – What can be controlled?

The use of test data in a logical sequence of reactions to modify a process and maintain a specified result is a process control strategy.

Before we discuss process control strategies, we need to understand that there are many interrelated factors that limit the performance of wastewater treatment plants. Performance limiting factors at wastewater treatment facilities can be broadly grouped in administration, design, operation and maintenance. Administration, design and maintenance all lead to a plant physically capable of achieving the desired performance. It is operation, or more specifically the process control that takes a physically capable plant and produces a good effluent. Figure 11.01 illustrates the relationship between physical limitations and operations (or process control).

---

<sup>3</sup> ORP discussion taken from materials produced by Ronald Schuyler.

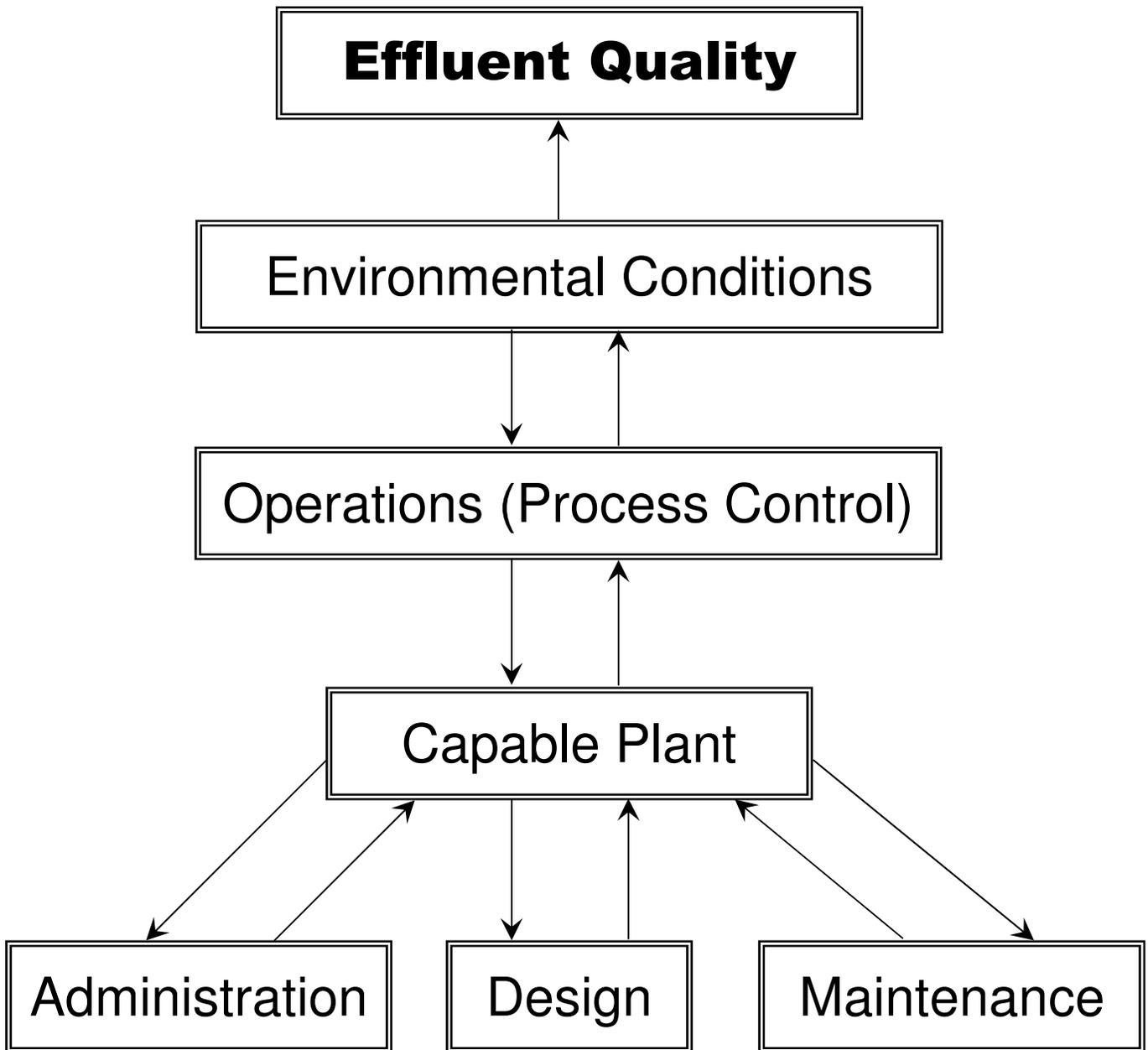


Figure 11.01

Given a plant that is physically capable including controllability of plant components, control strategies cannot be effective unless the plant operator:

1. monitors the process, and
2. utilizes the data to make logical decisions.

But, first we need to identify the variables which the operator has control over.

In the early years of activated sludge the general consensus was that the flocculated solids were the result of biological activity, and that these flocculated solids use oxygen. This represented a major breakthrough, because a relationship of oxygen to biological material represented a firm and distinct control mechanism for activated sludge. The concept of sludge production provided another major control mechanism for the process. We now call this production the sludge yield. Therefore, the second major control variable of the activated sludge process is the wasting of excess solids or wasting the yield from the process. A third major control variable that emerged was the return of settled sludge from the clarifiers to the aeration tank.

Figure 11.02, a diagram of a typical activated sludge plant, identifies the three major control mechanism for the activated sludge treatment process:

1. aeration rate,
2. return sludge rate, and
3. waste sludge rate.

Control of these three variables in addition to providing the proper environment (physical, chemical, biological and nutritional requirements) all lead to good sludge quality (see Figure 11.03).

## XII. AERATION RATE CONTROL – What are the control strategies?

There are two major reasons for adding air to an aeration tank. One reason is to keep the incoming wastewater and the activated sludge mixed. The other very important reason for adding air to the aeration tank is to provide dissolved oxygen. Dissolved oxygen (D.O.) is oxygen in water and is usually expressed in parts per million (ppm) or milligrams per liter (mg/L). Oxygen is not very soluble in water. At 20°C (68°F), only 9.2 mg/L of oxygen can be dissolved into the water.

Oxygen supply in an aeration tank must satisfy two needs: oxygen demand and residual D.O. Oxygen demand is the mass of oxygen required to meet BOD and nitrification, whereas, the required residual D.O. is the oxygen needed to provide an environment that produces good sludge quality.

In general, aeration rates which provide a D.O. of between 1.0 to 2.0 mg/L are best for maintaining efficient, healthy activated sludge organisms. The actual D.O. concentration

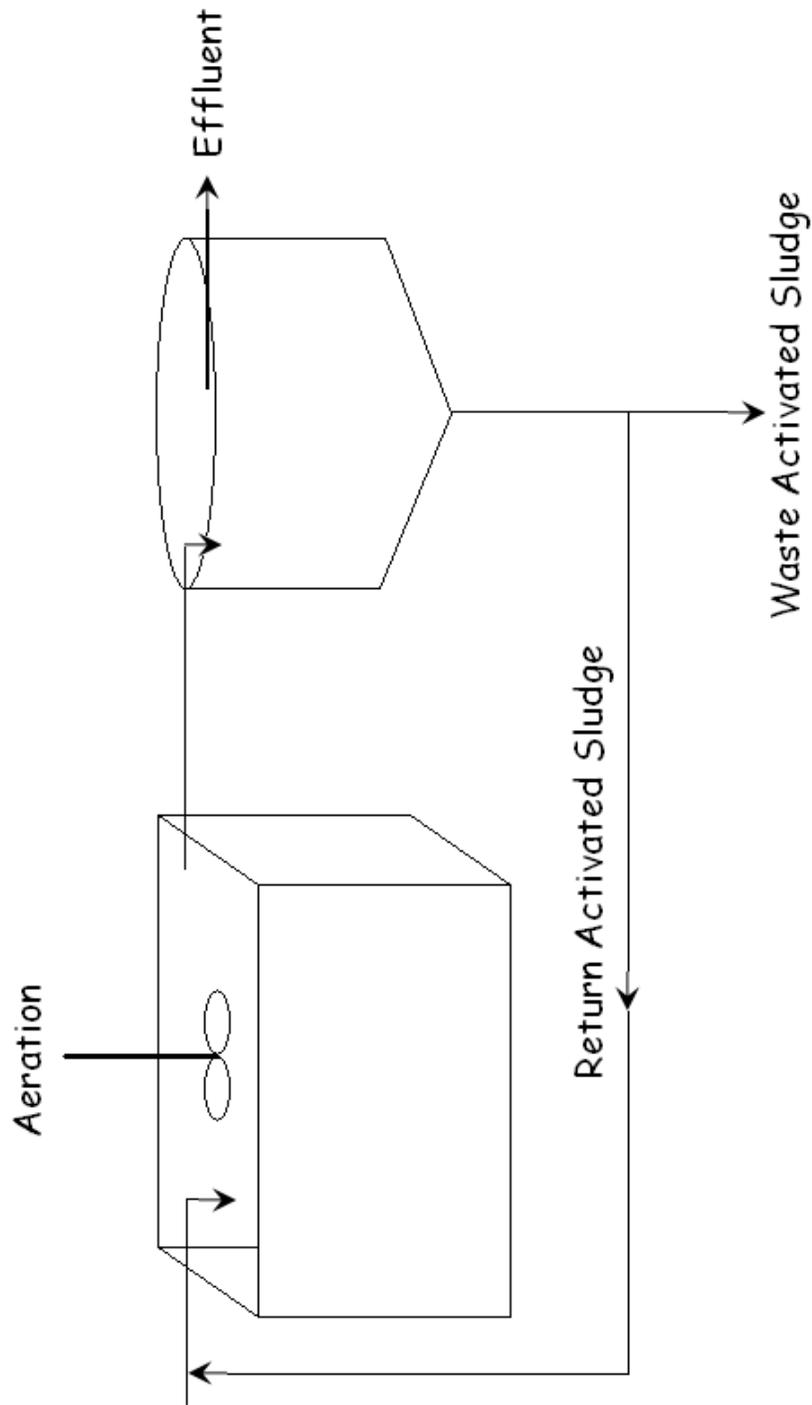


Figure 11.02

*Relationship of Process Control Variables*

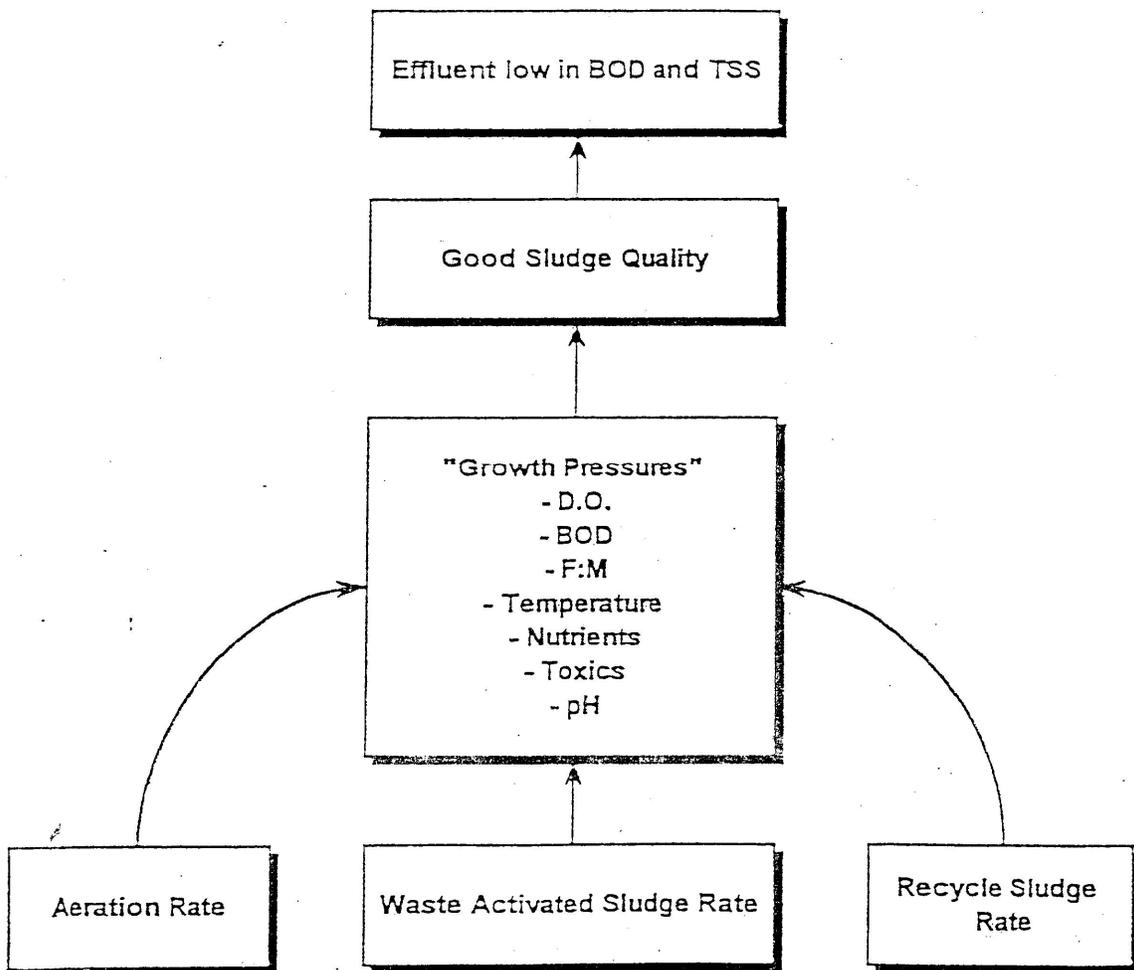


Figure 11.03

required depends on the F:M ratio. At high F:M ratios, the oxygen uptake rate is high and oxygen is depleted quickly from the bulk solution. This creates oxygen stress and therefore a higher D.O. residual is required at higher F:M ratios.

If the D.O. drops below 1.0 mg/L and especially below 0.5 mg/L, treatment efficiency will suffer. On the other hand, if the D.O. is maintained above 2.0 mg/L, a large amount of power is being wasted. Therefore, careful measurement and control of D.O. in the aeration tank is necessary.

Most aeration tanks will not have D.O. concentrations that are constant throughout the tank. There will be locations of high or low D.O. called stratification. Therefore, an aeration tank D.O. profile is necessary. A D.O. profile should be run 3 to 4 times per year and should include different times of the day.

Aeration rate control simply means using the D.O. profile information and adjusting the location of aerators or air flow rates to maintain the desired level of residual D.O.

There are many factors that may affect the oxygen requirements of the microorganisms in the aeration tank. One of the important relationships is between the influent BOD (food) and the oxygen demand.

As the influent BOD entering the aeration tank increases, the amount of oxygen required to maintain a desired level of D.O. also increases.

Another important relationship to remember involves the oxygen demand (utilized) and the degree of endogenous respiration.

As the endogenous respiration increases (extended aeration), the amount of oxygen required also increases. In other words, the oxygen uptake rate is decreased, but the total amount of oxygen increases due to the increased biomass needs for respiration.

The oxygen uptake test is one of the process control tools available to the operator. Besides monitoring the health of the biomass and its ability to treat wastes, the oxygen uptake test can also be used to calculate the oxygen consumption of the biomass. The oxygen consumption can be compared against the capacity of the aeration system. This may help determine if additional aeration capacity is required or if some other process adjustment is needed. See Appendix H for OUR/SOUR test procedures.

The fed and unfed tests use the simple OUR test on simulated sludges. Once the two tests have been completed, a ratio of fed over unfed is calculated. If the ratio is less than 1.0, a toxic effect is shown since the fed would be using oxygen slower than the unfed. A value of 1-2 is found with very dilute influents or with wastes that contain slowly degradable materials. A ratio between 2-5 is usually normal for a domestic waste while a value above 5.0 indicates extremely high loading. Industrial waste can greatly affect this ratio and their effects must be evaluated on a plant by plant basis. See Appendix H for fed/unfed test procedures.

### XIII. RETURN SLUDGE RATE CONTROL

Return sludge is the liquid pumped from the bottom of the final clarifier back to the aeration tank. If the liquid was not pumped from the bottom of the final clarifier, the solids would get deeper and deeper and deeper and soon flow over the effluent weirs. The return sludge is pumped back to the aeration tank to return the live, hungry bugs on the bottom of the clarifier back to the aeration tank to continue eating the incoming food.

The objective of return rate control is to optimize the distribution of solids between the aeration tank and final clarifier and to optimize both functions of the final clarifier: clarification and thickening.

Clarification is defined as the separation of solid particles and liquid. Thickening is defined as the increase in solid concentration in which particles move closer to each other.

To illustrate the objectives of return sludge rate control, let us consider what happens if the return was shut off:

- The sludge blanket would begin to rise and soon solids would go over the effluent weirs.
- The aeration basin solids level would decrease and result in an insufficient number of bugs to eat the incoming BOD.
- The solids in the final clarifier would quickly become anaerobic.

What would happen if the return was full open:

- The sludge on the bottom would be very thin.
- The increased return rate would increase the solids loading and decrease the settling time in the clarifier.

As you can see, the optimum rate is somewhere between full open and turned off. To begin discussing return rate control, we need to review typical return rates for various types of activated sludge processes as a percent of the incoming wastewater flow.

| Process               | Average | Lower Limit | Upper Limit |
|-----------------------|---------|-------------|-------------|
| Conventional          | 30      | 15          | 75          |
| Extended              | 100     | 50          | 200         |
| Contact Stabilization | 100     | 50          | 150         |

There are two basic methods for returning sludge to the aeration tank.

- At a constant rate, independent of the influent flowrate.
- At a constant percentage of the varying influent flowrate.

Advantages and disadvantages of constant rate versus constant percentage.

| Return Approach                 | Advantage  | Disadvantage  |
|---------------------------------|--|---|
| Return at constant rate         | <ol style="list-style-type: none"> <li>1. Simplicity</li> <li>2. Requires less operational time.</li> </ol>  | <ol style="list-style-type: none"> <li>1. F/M constantly changes</li> <li>2. Sludge blanket may approach clarifier surface during high flow.</li> </ol> |
| Return at a constant percentage | <ol style="list-style-type: none"> <li>1. MLSS held more constant and therefore F/M more constant.</li> <li>2. Sludge blanket tends to remain constant.</li> </ol> | <ol style="list-style-type: none"> <li>1. Complexity.</li> <li>2. Requires more operational attention.</li> </ol>                                       |

For either return flow rate control methods, there are a number of techniques that may be used to determine the optimum return sludge flow rate. The most commonly used techniques include:

- clarifier sludge blanket depth
- secondary clarifier mass balance
- aeration tank mass balance
- settleability
- SVI
- sludge quality
- state point analysis

There are advantages and disadvantages for all of the techniques.

| Technique         | Advantages  | Disadvantages   |
|-------------------|---|---|
| Sludge Blanket    | <ol style="list-style-type: none"> <li>1. Simplicity</li> </ol>               | <ol style="list-style-type: none"> <li>1. Does not optimize the thickening function.</li> </ol> |
| Mass Balance      | <ol style="list-style-type: none"> <li>1. MLSS held more constant.</li> </ol> | <ol style="list-style-type: none"> <li>1. Does not optimize the thickening function.</li> </ol> |
| Settleability/SVI | <ol style="list-style-type: none"> <li>1. Assumptions</li> </ol>              | <ol style="list-style-type: none"> <li>1. Laboratory test required.</li> </ol>                  |
| Sludge Quality    | <ol style="list-style-type: none"> <li>1. Optimize both</li> </ol>            | <ol style="list-style-type: none"> <li>1. Laboratory test</li> </ol>                            |

clarification & thickening functions. required.

State Point Analysis 1. Optimize both clarification & thickening functions. 1. Complexity

Clarifier Sludge Blanket Depth. Monitoring the depth of the sludge blanket in the clarifier is both quick and easy. The sludge depth should be checked on a routine basis at the same time (preferably during the period of maximum flow). The blanket depth should be kept to less than two feet. The blanket should never be allowed to rise beyond 25% of the nominal sidewall depth of the tank.

Secondary Clarifier Mass Balance. The mass balance approach is useful for calculating the return sludge flowrate necessary to maintain the solids distribution. However, it does assume that the system is operating at a steady state and that the sludge blanket in the secondary clarifier is constant. A side benefit of the mass balance approach is that, in plants without functioning return sludge metering, the return flow can be estimated from the measured mixed liquor and return concentrations. The calculations are based on a mass balance of suspended solids that enter and leave the secondary clarifier.

Solids entering the secondary clarifier can be estimated as:

$$\text{Solids in, lbs/day} = (\text{MLSS})(Q + Q_r)(8.34 \text{ lbs/gal})$$

where:

MLSS = mixed liquor suspended solids, mg/L

Q = influent flow, mgd

Q<sub>r</sub> = return flow, mgd

Assuming negligible solids in the effluent, the solids leaving equals:

$$\text{Solids out, lbs/day} = (\text{RASSS})(8.34 \text{ lbs/gal}) + (\text{WASSS})(Q_w)(8.34 \text{ lbs/gal})$$

where:

RASSS = return sludge suspended solids, mg/L

WASSS = waste sludge suspended solids, mg/L

Q<sub>w</sub> = waste sludge flow rate, mgd

Mass Balance:

$$(\text{MLSS})(Q + Q_r)(8.34) = (\text{RASSS})(Q_r)(8.34) + (\text{WASSS})(Q_w)(8.34)$$

$$(\text{MLSS})(Q + Q_r) = (\text{RASSS})(Q_r) + (\text{WASSS})(Q_w)$$

$$(MLSS)(Q) + (MLSS)(Q_r) = (RASS)(Q_r) = (WASSS)(Q_w)$$

$$(MLSS)(Q) - (WASSS)(Q_w) = (RASSS - MLSS)(Q_r)$$

$$Q_r = \frac{(MLSS)(Q) - (WASSS)(Q_w)}{RASSS - MLSS}$$

Example: Calculate the return sludge flow rate,  $Q_r$

Given:

$$Q = 1.0 \text{ mgd}$$

$$Q_w = 0.01 \text{ mgd}$$

$$MLSS = 2500 \text{ mg/L}$$

$$RASSS = 8000 \text{ mg/L}$$

$$WASSS = 8000 \text{ mg/L}$$

Solution:

$$\begin{aligned} Q_r, \text{ mgd} &= \frac{(2500)(1.0) - (8000)(0.01)}{8000 - 2500} \\ &= 0.44 \text{ mgd} \end{aligned}$$

**Aeration Tank Mass Balance.** From an aeration tank mass balance the solids entering the tank will equal the solids leaving the tank if new cell growth is considered negligible. The solids which enter the tank are estimated by:

$$\text{Solids in, lbs/day} = (RASSS)(Q_r)(8.34 \text{ lbs/day})$$

$$\text{Solids out, lbs/day} = (MLSS)(Q + Q_r)(8.34 \text{ lb/day})$$

Mass balance:

$$(Q_r)(RASSS)(8.34) = (MLSS)(Q + Q_r)(8.34)$$

$$Q_r = \frac{(MLSS)(Q)}{RASSS - MLSS}$$

**Settleability.** The setteability test can be used to estimate the desirable sludge return rate. This method uses the sludge volume in a 2-liter settleometer at the end of 30 minutes settling. The underflow,  $Q_r$ , is given according to the following equation:

$$Q_r = \frac{(SSV)(Q)}{1000 - SSV}$$

where,

SSV = volume of settled sludge after 30 minutes, ml/L

Example: Calculate the return sludge flow,  $Q_r$

Given: SSV 300 ml/L

$$Q = 1.0 \text{ mgd}$$

Solution:

$$Q_r = \frac{(300)(1.0)}{1000 - 300}$$

$$= 0.43 \text{ mgd}$$

SVI. The SVI method is a mass balance approach using the SVI to estimate the suspended solids concentration in the return. Using this technique,  $Q_r$  is given as:

$$Q_r = \frac{(\text{MLSS})(Q)}{1,000,000 - \text{MLSS}} \text{ SVI}$$

where:

$$\text{SVI} = \frac{(\text{SSV}_{30})(1000)}{\text{MLSS, mg/L}}$$

Example: Calculate the return sludge flow,  $Q_r$

Given: SVI = 120

$$Q = 1.0 \text{ mgd}$$

$$\text{MLSS} = 2500 \text{ mg/L}$$

Solution:

$$Q_r = \frac{(1.0)(2500)}{1,000,000 - 2500} \text{ SVI}$$

$$0.43 \text{ mgd}$$

Sludge Quality. At West of the U.S. EPA developed a method using the information from the settleability test and the sludge solids concentration. The figure 13.01 below shows three general types of sludge settleability: normal, rapid and slow.

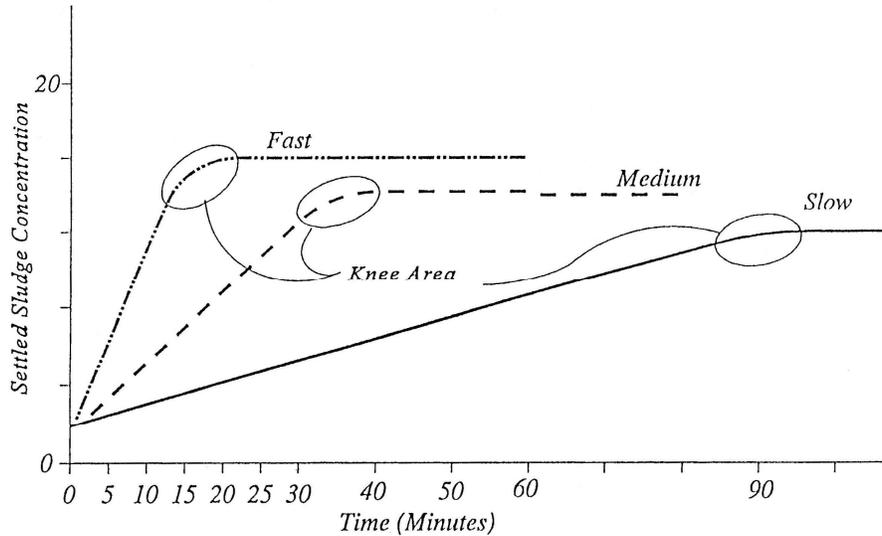


Figure 13.01

The sludge quality approach is used to establish the proper return rate so the RAS is removed quickly as well as thickly.

For a slow settling sludge, the optimum settling time is near the inflection point A on the curve where the increase in concentration begins to diminish. For normal and rapid settling sludges, the optimum is selected before the break (knee bend) which is shown as points B and C, respectively.

#### Steps of Sludge Quality Method

1. Determine the return sludge flow control requirement from the sludge quality and settled sludge concentration curves.
2. Force the return sludge concentration by proper return sludge flow adjustment to approach the settled sludge concentration given from the settled sludge concentration curves. Guideline values:

Rapid 15 – 30 min. settled sludge concentration (SSC)  
 Normal 40 – 60 min. settled sludge concentration (SSC)  
 Slow 100 – 140 min. settled sludge concentration (SSC)

The following equation is used to develop settled sludge concentration curves and can be used to calculate the optimum settled sludge concentration.

$$\text{Settled Sludge Concentration (SSC)} = \frac{\text{Aeration Tank Concentration (MLSS)} \times 1000 \text{ ml/l}}{\text{Settled Sludge Volume (SSV)}}$$

Example: Calculate the optimum settled sludge concentration, SSC

Given: From the daily settleability curves the optimum settling time is  $t = 40$  min., SSV at the end of 40 min. = 280 ml/L, ATC = 2500 mg/L, RSC = 8,000 mg/L.

Calculate SSC at 40 min.

$$\begin{aligned} \text{SSC}_{40} &= \frac{(2500)(1000)}{280} \\ &= 8,930 \text{ mg/L} \end{aligned}$$

In this example, the actual RSC of 8,000 mg/L is more dilute than the calculated optimum of 8930 mg/L, therefore, the return sludge flowrate should be decreased to concentrate the return until it approaches the optimum.

#### SUMMARY NOTES ON RETURN SLUDGE RATE CONTROL

1. The basic control strategy is: 1) maintain an optimal distribution of solids between the aeration tank and the secondary clarifier (solids belong in the aeration tank), 2) return the solids to the aeration tank quickly (avoid anaerobic conditions), and 3) optimize the sludge concentration (thickly).
2. Check your plant's current return sludge flowrate versus typical rates given for your mode of operation.
3. Select an appropriate control method (i.e., constant rate or constant percentage),
4. All plants should monitor the sludge blankets,
5. Return rate changes should be made whenever: 1) the average daily flow changes, or 2) the sludge settling characteristics change.
6. In most plants, there is a limit to how low the return sludge flowrate can be reduced before the return sludge piping plugs up.
7. Return sludge flow rate changes should be limited to +/- 15 to 25 percent per day.
8. System response to RAS flow changes are somewhat rapid. Normally, the system responds within  $\frac{1}{2}$  the aeration detention time.

#### XIV. WASTE ACTIVATED SLUDGE CONTROL

Sludge wasting represents the operator's greatest control adjustment. Sludge wasting affects the following:

- solids inventory
- F/M and Sludge Age
- the production of biological solids
- oxygen consumption
- mixed liquor settleability
- nutrient quantities needed
- the occurrence of foaming
- the possibility of nitrification

The fundamental reason that wasting is required in the activated sludge process is the fact that the net rate of MLSS cell formation exceeds the net rate of MLSS decay.

$$\text{Accumulation} = \text{inflow} - \text{outflow} + \text{netgrowth} - \text{endogenous decay}$$

These excess solids must be wasted in order to regulate the MLSS inventory at the desired F/M range. In addition to biological growth, inert non-biodegradable solids from the raw influent TSS tend to accumulate in the aeration basin and require wasting.

The objective of sludge wasting is to control the wasting rate to maintain steady state. In other words: wasting equals the accumulation of solids (net growth + inert non-biodegradable). If sufficient sludge is not wasted intentionally, it will waste itself in the final effluent until a process equilibrium is reached.

An example can be used to illustrate the concepts of sludge inventory, F/M, SRT and solids production.

Example: Calculate the F/M, SRT, and solids production.

Given:  $F = 100$  lbs/day  
 $M = 300, 100, 1000$  lbs  
 $Y = 0.55$   
 $K_d = 0.02$

Solution: 1a)  $F/M = \frac{100}{300}$   
 $= 0.33$

1b)  $\frac{1}{\text{SRT}} = Y(F/M) - K_d$   
 $\text{SRT} = \frac{1}{0.55(0.33) - 0.02}$   
 $= 6.2$  days

1c) solids accumulation =  $Y(F) - M(K_d)$   
 $= 0.55(100) - 300(0.02)$   
 $= 49$  lbs

1d)  $\text{SRT} = \frac{M}{W}$   
 $= \frac{300}{49}$   
 $= 6.1$  days

2a)  $F/M = \frac{100}{100}$

$$= 1.0$$

$$\begin{aligned} 2b) \text{ SRT} &= \frac{1}{0.5(1.0) - 0.02} \\ &= 1.9 \text{ days} \end{aligned}$$

$$\begin{aligned} 2c) \text{ solids accumulation} &= 0.55(100) - 100(0.02) \\ &= 53 \text{ lbs} \end{aligned}$$

$$\begin{aligned} 2d) \text{ SRT} &= \frac{M}{W} \\ &= \frac{100}{53} \\ &= 1.9 \text{ days} \end{aligned}$$

$$\begin{aligned} 3a) \text{ F/M} &= \frac{100}{1000} \\ &= 0.1 \end{aligned}$$

$$\begin{aligned} 3b) \text{ SRT} &= \frac{1}{0.55(0.1) - 0.02} \\ &= 28.6 \text{ days} \end{aligned}$$

$$\begin{aligned} 3c) \text{ solids accumulation} &= 0.55(100) - 1000(0.02) \\ &= 35 \text{ lbs} \end{aligned}$$

$$\begin{aligned} 3d) \text{ SRT} &= \frac{M}{W} \\ &= \frac{1000}{35} \\ &= 28.6 \text{ days} \end{aligned}$$

In this example, the aeration tank MLSS (M) at a given loading (F) is varied from 300, 100, to 1000 lbs. As shown, the F/M ratio varies from 0.33 (conventional), to 1.0 (high) and finally to 0.1 (extended). At these three loading rates, the net growth of biological solids (W) is 49 lbs., 53 lbs., and 35 lbs., respectively. This represents 0.49, 0.53 and 0.35 pounds of solids per pound of BOD.

Optimizing the activated sludge process depends on properly controlling the mass of active microorganisms in relationship to the loading. The mass of microorganisms is controlled by wasting solids. The four most common methods to determine the waste sludge rates are:

- constant MLSS
- constant F/M
- constant sludge age (SRT, MCRT)
- sludge quality

Constant MLSS. This technique is simple to understand and involves a minimum of laboratory work. It usually produces good quality effluent as long as the incoming wastewater characteristics are fairly constant. The initial step to use this technique is to determine the target MLSS concentration. The target MLSS should be selected by monitoring the process, observing trends and considering seasonal effects. Once a target MLSS is selected, the following procedure is used:

1. Measure the MLSS in each aeration tank, in mg/L, and average the results.
2. Measure the return sludge concentration, mg/L.
3. Calculate the mass to be wasted  

$$\text{MLSS to waste, lbs.} = (\text{Actual MLSS} - \text{Target MLSS})(V)(8.34)$$
 where V = aeration tank volume in million gallons
4. Calculate the volume of WAS:  

$$Q_w = \frac{(\text{MLSS})(1,000,000)}{(\text{RAS})}(8.34)$$

where  $Q_w$  = WAS, million gallons  
 MLSS = mixed liquor suspended solids to waste, lbs  
 RAS = return sludge concentration, mg/L

Example: Calculate the required wasting volume,  $Q_w$ , based on constant MLSS.

Given:

Aeration tank volume = 50,000 gallons  
 Actual MLSS = 2833 mg/L  
 Target MLSS = 2500 mg/L  
 RAS = 8000 mg/L

$$\begin{aligned} \text{MLSS to waste, lbs} &= (2833 - 2500)(0.05)(8.34) \\ &= 138.9 \text{ lbs} \end{aligned}$$

$$\begin{aligned} Q_w, \text{ gals} &= \frac{(138.9)(1,000,000)}{(8000)(8.34)} \\ &= 2080 \text{ gals} \end{aligned}$$

Constant F/M. This method requires a significant amount of laboratory work. Because it takes 5 days to get the results of the BOD analysis, a correlation between BOD and COD is desirable. Because it takes the process several days to fully respond to changes in conditions, the actual F/M should be calculated using a 7-day moving average. The target F/M should be within a desirable range to prevent upsets due to large swings in

wasting rates. For example: 0.02 units on either side of the target F/M for extended aeration and 0.05 units on either side for conventional.

The F/M ratio is expressed as:

$$F/M = \frac{\text{influent BOD, lbs/day}}{\text{solids in the aeration tank, lbs}}$$

The example below shows how to calculate the wasting rate,  $Q_w$ , to operate at a target F/M.

Given: Target F/M = 0.39  
 Influent BOD, F = 346 lbs/day  
 Actual MLSS, M = 1181 lbs/day  
 MLVSS/MLSS = 0.85  
 RASSS = 8000 mg/L

Solution:

$$\text{MLVSS to waste, lbs} = \frac{\text{actual MLVSS} - \text{influent BOD}}{\text{target F/M}}$$

$$= 117 \text{ lbs}$$

$$\text{MLSS to waste} = \frac{\text{MLVSS to waste}}{\text{MLVSS/MLSS ratio}}$$

$$\frac{117}{0.85}$$

$$= 138 \text{ lbs}$$

Constant SRT. The solids retention time (SRT) is widely used and reliable. The SRT is the average number of days that the microorganisms are kept under aeration. The expression for SRT is:

$$\text{SRT} = \frac{\text{Mass of solids under aeration}}{\text{Mass of solids leaving the system}}$$

The mass of solids leaving the system is defined as:

$$\text{solids out, lbs/day} = \text{SS wasted, lbs/day} + \text{SS in effluent, lbs/day}$$

The mass of solids under aeration is given as:

$$(\text{MLSS, mg/L})(V, \text{mg})(8.34)$$

The expression for SRT becomes:

$$\text{SRT} = \frac{(\text{MLSS})(V)(8.34)}{(\text{WASSS})(Q_w)(8.34) + (\text{ESS})(Q)(8.34)}$$

where:

WASSS = waste activated sludge suspended solids, mg/L

ESS = effluent suspended solids, mg/L

Q<sub>w</sub> = waste sludge flow, mgd

Q = influent flow, mgd

MLSS = mixed liquor suspended solids, mg/L

V = aeration tank volume, mg

Re-expressing for formula for SRT and solving for waste sludge, lbs/day.

$$\text{WAS, lb/day} = \frac{(\text{MLSS})(V)(8.34)}{\text{SRT, days}} - (\text{ESS})(Q)(8.34)$$

Example: Calculate the wasting rate, Q<sub>w</sub>

Given: WASSS = 8000 mg/L

Target SRT = 7 days

MLSS = 2833 mg/L

Effluent SS = 30 lbs/day

V = 0.05 mg

Solution:

$$\text{WAS, lbs/day} = \frac{(2833)(0.05)(8.34)}{7} - 30$$

$$= 139 \text{ lbs/day}$$

$$\text{Q}_w, \text{ gals/day} = \frac{(139)(1,000,000)}{(8000)(8.34)}$$

$$= 2083 \text{ gallons}$$

Sludge Quality Control. Using the sludge quality control method, the aeration tanks and final clarifiers are studied carefully for informative physical characteristics that help identify sludge quality and process status. The inferences of these physical findings are used to supplement the results of the other more specific control methods previously described. Using an integrated control strategy, the direction and magnitude of the control adjustments can be made. A basic concept of the method is that the best performance is achieved by satisfying all interrelated process requirements

simultaneously – not by exclusive dependence upon any single or preconceived factor. The control method includes the following observations and laboratory test:

- Aeration tank observations
- Secondary clarifier observations
- Microscopic examination of the MLSS
- Mixed liquor settling characteristics
- Depth of the sludge blanket
- MLSS respiration rates

#### Characteristics of Good Sludge Quality

1. Settles fairly rapidly as contrasted to a sludge that settles very fast or very slowly.
2. Concentrates uniformly in 30 to 60 minutes as contrasted to a sludge that concentrates very rapidly in less than 30 minutes or very slowly needing 2 hours or more.
3. Produces flocculent solids which form large strong flow particles which settle well, resist shear in the aeration tank and filter the supernate to remove stray particles.
4. Produces a clear supernate.
5. Is normally deep tan to light brown.
6. Normally has a pleasant musk or earthy odor.

#### Summary Notes on Waste Activated Sludge Rate Control

1. Waste sludge control has two goals: 1) excess accumulation of solids must be removed and 2) the appropriate sludge quality must be maintained.
2. System response to waste activated sludge rate changes are normally slow. Usually from about 1 to 2 SRTs.
3. Waste sludge changes should be limited to +/- 15 percent per day.

#### Summary – Process Control Strategies

In summary, while there are many different techniques to activated sludge process control, all of the methods are directed towards three common goals. First the operator must provide the proper environment in the system. For most municipal plants, this means providing adequate aeration and mixing. In industrial plant, this means providing the nutrients (nitrogen & phosphorus) requirements and adjusting the pH within the range of 6.0 to 8.5. Secondly, the operator must balance the mass of solids under aeration with the organic loading. The aeration tank F/M ratio provides a measure of the kinetics (growth rates) of the system. In plants where F/M is not monitored routinely, it is still implied by some other control parameter. For example, maintaining a given MLSS implicitly defines the F/M ratio. Finally, the operator must maintain a balance return sludge rate which allows mixed liquor thickening in the secondary clarifiers, yet also removing the MLSS rapidly enough to prevent septic sludge conditions.

## XV. PROCESS MONITORING

Monitoring the process is essential to successful process control. Organized and proper sampling, measurement, and data collection is used to make proper control decisions.

Monitoring tests are used to evaluate the performance of the system. Monitoring test include effluent quality test such as BOD and TSS. Process control test include observations of the aeration tank and secondary clarifiers, flow data, solids concentrations, sludge quality data, and environmental data. In addition, calculated data is required for aeration, return sludge and waste sludge (e.g., SRT). Data for plant process control and monitoring might include the following.

Flow:

- Influent/Effluent
- Return RAS
- Waste (WAS)
- Air
- Recycle Flows

BOD and COD:

- Influent/Effluent

TSS:

- Influent/Effluent

Observations:

- Aeration Tank
  - Spray patterns
  - Flow patterns
  - Turbulences
  - Color
  - Odor
  - Foam
- Secondary Clarifiers
  - Clarity
  - Bulking
  - Washout
  - Clumping/Ashing
  - Straggler floc
  - Pin floc

Solids concentration:

- Mixed liquor
- Return sludge

- Waste sludge
- Reaeration (for contact stabilization)

Sludge settling test data:

- Settled Sludge Volume (SSV)
- Settled Sludge Concentration (SSC)
- SVI
- Settling velocity
- Settling curves

Sludge blanket depth (for each clarifier)

Dissolved Oxygen DO:

- Aeration tank (inlet, midpoint, outlet)
- Reaeration tank (for contact stabilization)

Microscopic enumeration and characterization:

- Mixed liquor
- Return sludge

Turbidity

- Secondary effluent

Heavy metals

- Influent/effluent

SOUR (specific oxygen uptake rate)

- Aeration tank inlet/outlet (mixed liquor)
- Fed and unfed samples

Aeration Tank and Clarifier Oxygen Reduction Potential (ORP)

Nitrogen (ammonia TKN, nitrite, nitrate)

- Influent/effluent

Phosphorus

- Influent/effluent

## Alkalinity

- Influent/Effluent

Note: An alkalinity drop of more than 30 mg/L as CaCO<sub>3</sub> usually indicates nitrification.

As you can see there are many process evaluation and control test available to monitor and control the activated sludge system. The operator must decide which test are essential, how often to test, where to test and the sample type. Once the test have been selected, the operator must than identify common ranges or targets for the test data collected. An example process monitoring plan for a medium size plant (0.5 – 1.0 mgd) follows:

Process Mode: Extended Aeration

Log of Events

Loading Data

Avg. Daily BOD

Avg. Daily TSS

Detention Time – 20 hrs.

Aeration Tank Loading – 10 lbs/1000 ft<sup>3</sup>

Clarifier Solids Loading – 12 lbs/ft<sup>2</sup>

Clarifier Surface Overflow Rates – 220 gal/ft<sup>2</sup>

Return Rates – 100%

|  | Frequency | Location <sup>4</sup> | Sample Type | Common Range |
|--|-----------|-----------------------|-------------|--------------|
|--|-----------|-----------------------|-------------|--------------|

Flows:

|          |       |    |    |                 |
|----------|-------|----|----|-----------------|
| Influent | 99    | 1  | CN | -               |
| RAS      | 99    | 6  | CN | 50 – 200%       |
| WAS      | 01/BA | 6a | ES | 2700 – 3300 GPD |
| Recycle  | 01/BA | 6  | ES | -               |

Performance:

|           |       |     |    |   |
|-----------|-------|-----|----|---|
| BOD       | 02/07 | 1,5 | CP | - |
| TSS       | 02/07 | 1,5 | CP | - |
| Turbidity | 01/01 | 5   | CP | - |

Solids Concentration:

---

<sup>4</sup> See Figure 15.01 for a diagram of the process control test locations.

|               |       |      |    |                   |
|---------------|-------|------|----|-------------------|
| Mixed Liquor  | 03/07 | 2a,b | GR | 2250 – 2750 mg/L  |
| Return Sludge | 03/07 | 6    | GR | 6000 – 10000 mg/L |
| Waste Sludge  | 03/07 | 6a   | GR | 6000 – 10000 mg/L |

Sludge Quality:

|                    |       |      |    |                              |
|--------------------|-------|------|----|------------------------------|
| Observations       |       |      |    |                              |
| Color              | 01/01 | 2a,b | VI | -                            |
| Odor               | 01/01 | 2a,b | VI | -                            |
| Foam               | 01/01 | 2a,b | VI | -                            |
| Settling Test Data |       |      |    |                              |
| SSV                | 03/07 | 2b   | GR | -                            |
| SSC                | 03/07 | 2b   | GR | -                            |
| SVI                | 03/07 | 2b   | MC | 70 - 110                     |
| Settling Velocity  | 77/77 | 2b   | GR | -                            |
| Settling Curve     | 77/77 | 2b   | GR | -                            |
| Microscopic        |       |      |    |                              |
| Examination        | 02/07 | 2b   | GR | -                            |
| Respiration Rate   |       |      |    |                              |
| SOUR               | 77/77 | 2a,b | GR | 6-12 mgO <sub>2</sub> /hr/gm |

Environmental:

|                          |       |       |    |        |
|--------------------------|-------|-------|----|--------|
| Physical                 |       |       |    |        |
| Temperature              | 01/07 | 1,5   | GR | -      |
| Salinity                 | 77/77 | 1     | GR | -      |
| Oxygen/Mixing            | 02/07 | 2a,b  | GR | -      |
| Chemical                 |       |       |    |        |
| pH                       | 01/01 | 1,5   | GR | -      |
| acidity/alkalinity       | 77/77 | 1,5   | GR | -      |
| metals                   | 77/77 | 1     | GR | -      |
| other                    | 77/77 | 1     | GR | -      |
| Biological               |       |       |    |        |
| microscopic              | 02/07 | 2b    | GR | -      |
| Nitrogen (nitrification) |       |       |    |        |
| ammonia                  | 77/77 | 1,5   | GR | -      |
| TKN                      | 77/77 | 1,5   | GR | -      |
| nitrite                  | 77/77 | 1,5   | GR | -      |
| nitrate                  | 77/77 | 1,5   | GR | -      |
| Nutrition                |       |       |    |        |
| BOD/COD/TOC              | 77/77 | 1     | CP | -      |
| Oxygen                   | 02/07 | 2a,b  | GR | -      |
| Nitrogen/Phosphorus      | 77/77 | 5     | CP | -      |
| ORP                      | 77/77 | 2b, 4 | GR | 100 mV |

Aeration:

|                  |       |      |    |            |
|------------------|-------|------|----|------------|
| Observations     |       |      |    |            |
| Spray Patterns   | 01/01 | 2a,b | VI | -          |
| Flow Patterns    | 01/01 | 2a,b | VI | -          |
| Turbulences      | 01/01 | 2a,b | VI | -          |
| Dissolved Oxygen |       |      |    |            |
| Aeration Tank    | 01/01 | 2a,b | VI | 1 – 2 mg/L |

Return:

|                          |       |     |    |            |
|--------------------------|-------|-----|----|------------|
| Clarifier Sludge Blanket |       |     |    |            |
|                          | 05/07 | 4   | MS | 1 – 2 feet |
| Mass Balance             | 03/07 | 2,4 | MC |            |
| Settleability            | 03/07 | 2,4 | MC |            |
| SVI                      | 03/07 | 2,4 | MC |            |
| Sludge Quality           | 03/07 | 2,4 | ES |            |
| State Point Analysis     | 77/77 | 4   | MC |            |

Sludge Inventory (Wasting):

|                   |       |    |    |                  |
|-------------------|-------|----|----|------------------|
| Constant MLSS     | 03/07 | 2b | MC | 2250 – 2750 mg/L |
| F:M               | 77/77 | 2b | MC | 0.06 – 0.07      |
| Sludge Age (MCRT) | 03/07 | 2b | MC | 22 – 26 days     |
| Sludge Quality    | 03/07 | 2b | ES | -                |

Secondary Clarifier:

|                 |       |   |    |   |
|-----------------|-------|---|----|---|
| Observations    |       |   |    |   |
| Clarity         | 05/07 | 4 | VI | - |
| Bulking         | 05/07 | 4 | VI | - |
| Washout         | 05/07 | 4 | VI | - |
| Clumping/Ashing | 05/07 | 4 | VI | - |
| Straggler Floc  | 05/07 | 4 | VI | - |
| Pin Floc        | 05/07 | 4 | VI | - |
| Gasification    | 05/07 | 4 | VI | - |

CN = Continuous

ES = Estimate

CP = Composite

VI = Visual

GR = Grab

MC = Math Calculation

99 = Continuous

01/BA = Once per batch

02/07 = Twice per week

01/01 = Once per day  
03/07 = Three per week  
77/77 = Contingent  
05/07 = Five per week

Figure 15.01

## XVI. TROUBLESHOOTING

Good troubleshooting techniques are important for meeting performance objectives in the most cost effective manner. Troubleshooting is a step-by-step procedure to diagnose and correct a problem.

Troubleshooting consists of seven major activities:

- Recognizing that a problem exists.
- Assigning priorities to ensure that each problem receives adequate attention.
- Gathering facts in an organized manner to establish base data.
- Finding the cause of the problem as quickly as possible to minimize the impact on process and cost.
- Identifying possible alternative courses of action.
- Recording the facts in an organized manner.
- Eliminating or reducing the cause of the problem to minimize recurrence.

The first step in troubleshooting is to recognize that there is a problem. All plants should have Standard Operating Procedures (SOP's) which include procedures for operators to detect problems. The ability to recognize minor problems and to correct them early can prevent them from developing into major problems.

Once a problem is detected, an assessment must be made as to its priority over other existing problems. The three major factors in assigning priorities are seriousness, urgency, and growth of the problem in terms of impact on process performance or safety of personnel or equipment.

Gathering facts is a four-step process: stating the problem, defining the boundaries, noting differences and changes, deciding on cause/effect.

**Problem statement.** The problem statement should be a precise description of the problem in terms of observable facts.

**Boundary definition.** Ask the following types of questions: Where is the problem observed? When was the problem first detected? What is the extent of the problem?

**Differences and Changes.** Note any difference or changes from what is normal.

**Cause/effect.** Identify probable cause

Possible alternative courses of action may be from the following five categories: contingent, interim, corrective, adaptive and preventive.

Contingent actions. These are taken immediately to minimize the effect of the problem.

Interim actions. Interim actions are taken while the problem is being solved and repairs are being made.

Corrective actions. Corrective actions address the cause of the problem.

Adaptive actions. Adaptive actions allow the plant to live with the problem.

Preventive actions. These reduce or eliminate the cause of a problem.

Procedure needs to be established to ensure that facts are recorded so that:

- Important facts are not lost when a problem occurs.
- The cause of a problem is more quickly isolated.
- Management is provided with the records.
- Engineering is provided with the data to analyze alternatives.

The establishment of a good process control strategy and monitoring program is essential to troubleshooting the activated sludge process. Before troubleshooting a problem it is important to review the plant's physical capabilities and limitations. A design audit should be conducted. The design audit should include:

1. Plant loading
  - a. Organic
  - b. Hydraulic
  - c. Industrial
  - d. Toxic
  - e. Seasonal variations
  - f. Infiltration/inflow
  - g. Return process streams
2. Plant layout
3. Flow measurements
4. Bar Screens
5. Comminutors
6. Grit Removal
7. Primary Clairfiers
8. Aeration
  - a. Hydraulic detention time
  - b. BOD loading
  - c. Oxygen availability

9. Secondary clarifier
  - a. Surface overflow rates
  - b. Solids loading rates
  - c. Depth at weirs
  - d. Possible RAS flow range
  - e. Short circuiting
10. Solids handling

Operational problems which are commonly experienced are:

1. Aeration. The operator should observe the entire aeration tank for turbulence. The extent of turbulence will indicate whether or not all sewage, return sludge, and mixed liquor are thoroughly mixed throughout the tank.
2. Foaming. The type of foam or scum, if any, accumulated over the aeration tank surface and to a lesser extent the color of the mixed liquor reveals process status and indicates generalized long-term sludge wasting requirements.
3. Solids Washout. Excessive solids washout over the final effluent weirs, when the upper surface of the sludge blanket is more than three feet below the clarifier surface and when the sludge settles properly in the laboratory, should not be confused with classic sludge bulking. Solids washout, which differs from classic sludge bulking, is more frequently caused by hydraulic overloading, toxic substances (such as high pH, heavy metals, phenols, etc.) or inappropriate secondary clarifier design.
4. Bulking. Such conditions are evidence by a homegenous appearing sludge blanket that extends throughout the entire clarifier, and can be observed at the surface while the mixed liquor solids pour over the final effluent weirs.
5. Clumping/rising sludge. At times, large masses of sludge, possibly one foot in diameter, may be seen rising, then bursting, and finally spreading over the clarifier surface.
6. Cloudy secondary effluent. Secondary effluent is cloudy and contains suspended matter.
7. Ashing. Small particles of ash-like material floating on the surface of the clarifier and in mixed liquor settleability test.
8. Pinpoint floc. Very small, compact pin floc, usually less than on thirty-second of an inch in diameter, may be observed suspended throughout moderately turbid final clarifier tank contents.
9. Straggler floc. Small, almost transparent, very light fluffy, buoyant sludge particles (one eighth to one-quarter inch in diameter) may be observed rising to the clarifier surface near the outlet weirs.

The tables in Appendix O list observations, probable causes, necessary checks and alternatives for these operational problems.

When troubleshooting process problems at an activated sludge plant, it is important to proceed in an organized manner and to check all of the possibilities.

Figure 16.01 shows a diagram of the troubleshooting process. First, the problem(s) are identified using tools such as brainstorming. Next, a problem is selected and described. A written statement of the problem is prepared. Baseline data is gathered and

Figure 16.01

summarized. Tools include multivoting, selection grid, impact analysis, data-gathering, run charts, Pareto analysis, and control charts.

Next is the expansion and analysis of the cause. This phase starts with analysis of the problem from data. A list of the most influential factors is developed and priorities are identified. The tools for this step include data-gathering, sampling, surveys, Pareto analysis, fishbone diagram, flow charts, control charts, relationship analysis.

The third step is the expansion and development of the solution(s) and plan. The output of this phase is a solution(s) to the problem and a plan for implementation. The tools include technology transfer, cost-benefit analysis, and force field analysis.

The final step is the execution and implementation of the plan. The outputs include organizational commitment, an executed plan, and a record of the plan's impact. The tools include building individual support, presentations, measuring and monitoring, descriptive charts, specifications and control limits.

In addition to organizing thoughts on process control figures 11.01 and 11.03 can serve as a guide to troubleshooting.

The first step is to define the problem in terms of effluent quality. Next, check the environmental conditions ("growth pressures"), such as D.O., BOD loading, MLSS/MLVSS, F:M, temperature, nutrients, toxins, hydraulics (detention time), alkalinity, ORP, and pH. Next check the process control. This includes good sludge quality, such as aeration tank/secondary clarifier observations, sludge settling (diluted settleability), microbiology and respiration rate. Using the microscope check the viability, floc size, filaments (amount and type), and predominant form of protozoa/metazoa. And finally check the process control parameters. Check the aeration tank dissolved oxygen at the inlet/outlet and midpoint. Check the sludge blanket depth. Check the MLSS, F:M and SRT/MCRT. If the process control looks good, check the physical capability of the process. This includes administrative, design and maintenance factors.

Administrative factors include: 1) policies, 2) staffing, and 3) financial. Maintenance factors include: 1) housekeeping, 2) scheduling & recording, 3) preventive maintenance, and 4) emergency. See the EPA Handbook on Improving POTW Performance Using the Composite Correction Program Approach, October 1984.

Problems associated with the activated sludge process can usually be related to four conditions (Schuyler, 1995). The first is foam, the second is high effluent suspended solids, the third is high concentrations of soluble materials (BOD and ammonia) and the fourth is a general problem related to low effluent pH. See Appendix P for a section on

Troubleshooting Activated Sludge Processes that was prepared for the Maine DEP and JETCC by Ronald Schuyler, P.E., Rothberg, Tabburini, and Winsor (RTW).

Foam problems can be summarized as:

- Pumice-like – Solids Return
- Grey, Thick, Slimy – Nutrient Deficiency
- Dark Brown, Thick, Scummy – Old sludge
- Billowy White – Surfactant
  - Plant Start-up
  - High Surfactant load

Excess effluent suspended solids:

- Blanket Washout
  - Controllable Settling
  - Uncontrollable Settling
- Individual Particle
  - Pin-Floc
  - Straggler Floc
- Controllable Settling
  - Hydraulic Overload
  - Inadequate sludge return
- Uncontrollable Settling
  - Good Settling with Diluted Settleometer
    - Excess old sludge
    - Glutted system
  - Poor Settling with Diluted Settleometer
    - Bulking
    - Slime
    - Filamentous
- Filamentous Problems
  - Foam Trapping
  - Low D.O.
  - Low pH
  - Nutrient Deficiency
  - Sulfides
  - Readily Metabolized Substrate
  - Slowly Metabolized Substrate
  - Surface Seeding
- Individual Particle Washout
  - Pin Floc
    - High MCRT

- Grossly Underloaded Plant
- Clarifier Denitrification
  - Recycle from Solids Processing
- Straggler Floc
  - Filamentous
  - Nonfilamentous
- Individual Bacterial Cells
  - High SOUR, Young sludge
  - Low SOUR, Toxic load

#### Excess BOD<sub>5</sub> or NH<sub>3</sub>

- Very Low respiration Rate
  - Toxic Load
- 0.0 Respiration Rate
  - Microorganisms Killed
- Low Respiration Rate
  - Inhibition
- Medium-High SOUR
  - Material Difficult to Stabilize
  - Slight inhibition
- High SOUR
  - Hydraulic Overload for Given SDT
  - Organic Overload for Given Biomass

#### Low Effluent pH

- Low influent pH
- Normal influent pH – Nitrification
  - Nitrification required
  - Nitrification not required

## XVII. GLOSSARY

|                          |  |
|--------------------------|--|
| Absorption               | The use of oxygen, water, and organic matter for the metabolism of the organisms.  |
| Accuracy                 | Correctness. When doing laboratory testing, accurate results are values that are close to the true value.  |
| Acid                     | A chemical compound that forms hydronium ions in water, the resultant solution has a pH less than 7.   |
| Acid-forming bacteria    | Anaerobic bacteria that produce volatile acids as a waste product.   |
| Acidity                  | The ability of a solution to react with or neutralize a strong base to a specific pH. Measured in terms of mg/L CaCO <sub>3</sub> (calcium carbonate).   |
| Activated Sludge         | Activated sludge is a brownish floc-like material consisting largely of organic matter obtained from the sewage. This material is inhabited by millions of bacteria and other forms of biological life, mainly aerobic in nature.  |
| Activated Sludge Loading | The pounds of biochemical oxygen demand (BOD) in the applied liquid per unit volume of aeration capacity or per pound of activated sludge per day.   |
| Adsorption               | The adherence of dissolved, colloidal or finely divided solids on the surface of the solid bodies with which they are brought into contact.  |
| Aeration                 | The bringing about of intimate contact between air and liquid by one of the following methods: spraying the liquid into the air; bubbling air through the liquid, or by agitation of the liquid to promote surface adsorption of the air; or any combination of these methods. |

|                                   |   |
|-----------------------------------|---|
| Aeration Period                   | The theoretical time, usually expressed in hours during which mixed liquor is subjected to aeration in an aeration tank while undergoing activated sludge treatment. It is equal to the volume of the tank divided by the volumetric rate of flow |
| Aeration Rate                     | The amount of air supplied to the mixed liquor, measured in cubic feet per minute (cfm) for diffused aeration and measured in and horsepower for surface aeration.  |
| Aeration Tank Concentration (ATC) | The concentration of solids under aeration. Another term for MLSS. of the wastewater.   |
| Aerator                           | A structure, round or rectangular built for the purpose of aerating and mixing activated sludge liquor.   |
| Aerobic                           | Environmental conditions that contain free dissolved oxygen.  |
| Aerobic Digestion                 | Sludge stabilization using aerobic microorganisms, free oxygen must be available.   |
| Aerobic Respiration               | Respiration process that uses free molecular oxygen.  |
| Air Cleaner                       | A device for removing foreign material from the air that is used for aeration through diffusers.  |
| Air Diffusers                     | Devices for breaking up air into fine bubbles in water for the purpose of transferring a part of the oxygen in the air to the liquid surrounding the bubble.  |
| Alkaline                          | A solution with a pH greater than 7.0.  |
| Alkalinity                        | Buffering, or acid neutralizing capacity of water primarily due to its carbonate, bicarbonate, and hydroxide content. Measured in mg/L of CaCO <sub>3</sub> (calcium carbonate).  |

|                       |  |
|-----------------------|--|
| Ambient temperature   | Temperature of the surroundings.   |
| Anabolism             | Chemical reaction forming molecules within a bacterial cell.   |
| Anaerobic Respiration | Respiration process that uses chemically combined oxygen.  |
| Anoxic                | A condition in which oxygen is absent and nitrate is present.  |
| Area                  | A measurement of the amount of surface of an object; measured in linear units squared (for example, sq ft).  |
| Arithmetic Average    | The sum of a group of numbers divided by how many numbers there are in the group.  |
| Ashing                | In activated sludge, small particles of sludge which look like ash on the surface of the secondary clarifier. Usually indicates the beginning in nitrification.                            |
| Assimilation          | The process by which food is converted to cell protoplasm.   |
| Autotroph             | An organism that can use sunlight or inorganic chemicals as energy sources; these are photosynthetic and chemosynthetic organisms.   |
| Bacteria              | Single-celled microorganisms of primary importance in most biological wastewater treatment processes. They are the first step in removing most of the fine suspended and dissolved solids. |
| Baffle                | A structure that directs the wastewater flow or retains floating materials.  |
| Barminutor            | A preliminary treatment shredding device in which the shredding mechanism moves up and down the bar screen.  |

|                                 |   |
|---------------------------------|---|
| Bar Screen                      | An arrangement of uniformly spaced, parallel bars placed in the influent stream to catch large objects.   |
| Base                            | A chemical compound that forms hydroxide ions in water; the resultant solution has a pH greater than 7.   |
| Billowing Sludge                | Indicates the potential for solids washout in the activated sludge secondary clarifier. Can be identified by localized clouds of sludge solids rising near the surface in certain areas of the clarifier. |
| Biochemical Oxygen Demand (BOD) | The quantity of oxygen required by bacteria to biologically oxidize material under aerobic conditions.  |
| Biodegradation                  | The destruction or mineralization of organic materials by microorganisms.   |
| Bioflocculation                 | A condition whereby organic materials tend to be transferred from the dispersed form in wastewater to settleable material by mechanical entrapment and assimilation.                                      |
| Biomass                         | Active or dead microorganisms present in a particular area of a biological treatment plant.   |
| Biosorption                     | An application of the activated sludge process where the returned activated sludge is aerated for a prolonged time.   |
| Blanket Thickness (BLT)         | The measurement from the bottom of the clarifier to the top of the sludge blanket, usually determined with a core sampler or electronic interface detector.   |
| Bulking                         | A condition in which activated sludge does not concentrate and will not settle well (SVI>150).  |
| Carbonaceous Oxidation          | Biochemical process by which heterotrophic microorganism derive energy from organic wastes, rendering more stable organics or inorganics end-products.  |

|  |   |
|--|---|
| Catabolism                             | Chemical reaction breaking down molecules within a bacterial cell.  |
| Catalyst                               | A substance that speeds up a chemical reaction without being altered itself.  |
| Chemical Oxygen Demand (COD)           | The amount of oxygen required for the chemical oxidation of organic material using chemicals as oxidants.   |
| Ciliate                                | A type of protozoan characterized by short hairlike filament (cilia) used for motility and/or capturing food.   |
| Clarifier                              | Tank in which suspended solids are allowed to separate from water by gravity settling.  |
| Clarifier Sludge Detention Time (CSDT) | The time sludge remains in a secondary clarifier.   |
| Clarifier Sludge Flow (CSF)            | The sludge flow rate from the secondary clarifier.  |
| Clarifier Sludge Flow Demand           | Refers to the return rate which allows sludge to thicken in the clarifier based on its settling characteristics.  |
| Colloids                               | Finely divided, nonsettleable solids which may be removed by coagulation or biochemical action.   |
| Comminutor                             | A device used to shred materials entering with the influent.  |
| Complete Mix                           | Idealized continuous flow reaction in which fluid particles are immediately dispersed throughout the reactor.   |
| Contact Stabilization Process          | A modification of the activated sludge process in which wastewater is aerated with a high concentration of activated sludge for a short period usually less than 60 minutes to obtain BOD removal. The solids are subsequently separated by sedimentation and transferred to a stabilization tank where aeration is continued, starving the activated sludge before returning it to the aeration basin. |

|                               |  |
|-------------------------------|--|
| Conventional Activated Sludge | An aerobic biological sewage treatment process in which a mixture of sewage and activated sludge is separated from the treated sewage (mixed liquor) by sedimentation and wasted or returned to the process as needed. The treated sewage overflows the weir of the settling tank in which separation from the sludge takes place. |
| Decant                        | (1) To draw off liquid without disturbing the sediment or the lower liquid layers. (2) To pour from one vessel into another.   |
| Deflocculation                | The break up of flocculated sludge particles; often results in pin floc and/or ashing.   |
| Denitrification               | The reduction of nitrates to nitrites and nitrogen gas.  |
| Depth of Blanket (DOB)        | The distance from the clarifier water surface to the top of the sludge blanket. When subtracted from the total clarifier depth, this should equal the blanket thickness (BLT).   |
| Detention Time                | The time it takes to fill a tank at a given rate of flow.  |
| Diffuser                      | A device which divides air into minute bubbles for diffusion into liquids.   |
| Digestion                     | The process of sludge stabilization that reduces the sludge volatile content and destroys most pathogenic microorganisms.  |
| Dissolved Oxygen (D.O.)       | The amount of oxygen dissolved in water, usually measured in aeration tanks and expressed in mg/L.   |
| Dissolved Solids              | Material that passes through a filter in a laboratory test. Dissolved solids must be measured by evaporation.  |
| Endogenous Decay              | A reduced level of respiration in which materials previously stored by the cell are oxidized.  |

|                                   |  |
|-----------------------------------|--|
| Endogenous Respiration            | Utilization of internal cellular material as food under aerobic conditions when an adequate external food supply is unavailable.               |
| Enzyme                            | A biological catalyst that speed up or makes a reaction occur without being changed itself.  |
| Extended Aeration                 | The activated sludge modification that operates in the endogenous respiration zone. The aeration detention time is usually about 24 hours.     |
| Facultative Organisms             | Bacteria that can utilize either free dissolved oxygen or chemically combined oxygen under aerobic or anaerobic conditions.                    |
| Field Transfer Rate (FTR)         | The actual oxygen transfer rate applied in the field.  |
| Flocculation                      | Gathering together of fine particles to form larger particles that are heavier and more easily settled.  |
| Food-to-Microorganism Ratio (F/M) | A mathematical calculation of the mass of food, measured as BOD, divided by the mass of solids under aeration, or MLSS.                        |
| Facultative                       | Refers to organisms that are able to function both in the presence or absence of free oxygen.  |
| Heterotrophic                     | An organism that consumes and decomposes organic mater as an energy source.  |
| Hi-Rate Activated Sludge          | A new variation of the conventional activated sludge process where faster and better treatment can be obtained through better controls.        |
| Hydraulic Detention Time          | The theoretical time required to displace the contents of a tank or unit at a given discharge rate (volume of tank divided by discharge rate). |

|                                 |   |
|---------------------------------|---|
| Hydrogen Sulfide                | A gas (molecular formula H <sub>2</sub> S) which produces a characteristic “rotten egg” odor.   |
| Imhoff Cone                     | Laboratory glassware used in settleable solids testing of sample with low solids concentrations.  |
| Inorganic                       | Material such as sand, salt, iron, calcium, and other mineral materials which are not converted in large quantities by microorganism action. Inorganic materials are chemical substances of mineral origin and may contain carbon and oxygen. |
| Log Growth Phase                | The period of time when the mass of microorganism is doubling in regular intervals. Food supply is not limiting, therefore, increases in population size are geometric.   |
| Mean Cell Residence Time (MCRT) | A mathematical determination of the length of time activated sludge bacteria spend in the system, expressed in days.  |
| Mechanical Aeration             | The transfer of oxygen from the air to the liquid by mechanical means. Such as mixing, spraying or pumping.   |
| Mesophilic                      | Operationally, the temperature range most conducive to the maintenance of optimum digestion by mesophilic bacteria; generally accepted as between 27° and 32°C.   |
| Metabolism                      | The process in which bacteria break down organic matter releasing energy and producing waste products.  |
| Methane                         | The flammable gas produced from the anaerobic decomposition of organic matter.  |
| Microonutrients                 | Inorganic nutrients required in only trace amounts.   |
| Microorganisms                  | Small organisms that can only be seen with a microscope.  |

|  |   |
|--|---|
| Mixed Liquor                                   | Contents of aeration tank which is the combination of aeration tank influent and return sludge.   |
| Mixers   | Mechanical equipment designed to mix the liquor in the aerator.   |
| Mixed Liquor Suspended Solids (MLSS)           | The mass of solids contained in the mixture in an aeration tank, determined by laboratory analysis.   |
| Mixed Liquor Volatile Suspended Solids (MLVSS) | The volatile or organic portion of the mixed liquor suspended solids, determined by laboratory analysis.  |
| Nematode                                       | Unsegmented worm.   |
| Nitrate  | A stable form of oxidized nitrogen; chemical formula $\text{NO}_3^-$ .  |
| Neutral Solution                               | A solution that is neither acidic nor basic; a solution with pH 7.  |
| Nitrification                                  | The biochemical conversion of ammonia to nitrate.   |
| Nitrite  | The unstable intermediate nitrogen compound between ammonia and nitrate; chemical formula $\text{NO}_2^-$ .   |
| Nitrogen                                       | An element required for growth and reproduction by organisms. Nitrogen in wastewater is available in forms of nitrate, nitrite, ammonia, and organic nitrogen. Kjeldahl nitrogen is the combined concentration of ammonia and organic nitrogen. Total oxidized nitrogen is the sum of the nitrite and nitrate nitrogen. |
| Nutrients                                      | Substances that are required to support living organisms. Nitrogen and phosphorus are commonly referred to as nutrients.  |
| Organic  | Substances that are of plant or animal origin.  |
| Organic Loading                                | The pounds of BOD applied to each 1000 gallons of a process.  |

|                                  |   |
|----------------------------------|---|
| Organic Nitrogen                 | Sources of organic nitrogen may be natural, such as proteins and urea. Today there are a number of sources of synthetic organic nitrogen.   |
| Oxidation                        | The addition of oxygen, removal of hydrogen, or the removal of electrons from an element or compound.   |
| Oxygen                           | The gas required by most plants and animals to break down organic matter for energy.  |
| Oxygen Transfer Efficiency (OTE) | The efficiency at which oxygen is transferred to water.   |
| Oxygen Uptake Rate (OUR)         | The rate at which dissolved oxygen is used by the microorganisms.   |
| Oxygen Utilization               | The oxygen consumed to support aerobic biological treatment processes.  |
| pH                               | A term used to express the intensity of the acid or alkaline sources. A pH of 7 is considered neutral, with acidity increasing as the pH decreases. Normal pH for wastewater treatment is 6.5 to 7.5. |
| Phosphorus                       | The nutrient that usually limits the productivity of a body of water.   |
| Photosynthesis                   | The use of sunlight by plants to obtain the energy necessary to synthesize new cell material.   |
| Pin Floc                         | Very fine floc particles with poor settling characteristics. Usually associated with old, overoxidized mixed liquor.  |
| Plant Balance                    | When all factors such as food supply, MLSS, D.O., and detention time are in the correct proportions, the plant is said to be in balance.  |

|                   |   |
|-------------------|---|
| Plug Flow Reactor | Idealized continuous flow reactor in which fluid particles are discharged in the same order in which they entered.  |
| Pre-Aeration      | A preparatory treatment of sewage, comprising aeration to add oxygen to the sewage, to promote the flotation of grease and to aid coagulation of the solids.  |
| Precision         | When doing laboratory testing, precise results are produced when there is a high degree of agreement between repeated measurements from a single sample. It is possible to have precision without accuracy.   |
| Primary Treatment | The first phase of wastewater treatment, consisting of separating the readily settleable or floatable solids by sedimentation and skimming. A physical form of treatment.   |
| Process           | A sequence of operations.   |
| Process Control   | Deliberate efforts to regulate the F/M ratio in activated sludge processes; any systematic effort to regulate process performance.  |
| Protoplasm        | The material of a living cell.  |
| Protozoa          | Microscopic animals.  |
| Q                 | A term used for plant flow rate.  |
| Reaeration        | The absorption of oxygen by a liquid where the D.O. has been depleted, such as reaerating the returned activated sludge for considerable time to promote the aerobic digestion of the solids adsorbed. Use with the biosorption activated sludge process. |
| Recirculation     | The absorption of oxygen by a liquid where the D.O. has been depleted, such as reaerating the returned activated sludge for considerable time to promote the aerobic digestion of solids adsorbed. Use with the biosorption activated sludge process.     |

|                                    |  |
|------------------------------------|--|
| Respiration                        | The biological activity of utilizing oxygen and releasing carbon dioxide.  |
| Return Activated Sludge (RAS)      | The settled or concentrated activated sludge solids collected from the secondary clarifier bottom and returned back to the aeration tank.                    |
| Return Sludge Flow (RSF)           | The hydraulic rate at which sludge is returned from the clarifier to the aeration tank.  |
| Rising Sludge                      | A problem in secondary settling tanks; generally attributed to denitrification in the sludge blanket.  |
| Rotifer                            | A small multicelled animal that gets its name from the rotating action of rows of cilia near its mouth.  |
| Secondary Treatment                | Phase of wastewater treatment in which dissolved and suspended material is converted into a form more readily separated from the wastewater.                 |
| Sedimentation                      | The process of settling suspended solids by gravity.   |
| Septic                             | A condition produced by the growth of anaerobic organisms . If severe, the wastewater turns black, giving off foul odors and creating a heavy oxygen demand. |
| Settleability                      | A measure of the tendency of mixed liquor suspended solids to settle.  |
| Settleable Solids                  | The matter in wastewater that will not stay in suspension during a preselected settling period.  |
| Settled Sludge Concentration (SSC) | The concentration of settled sludge based on the volume occupied in the settlometer.   |
| Settlometer                        | A wide-mouthed graduated cylinder used to evaluate settling properties of activated sludge.  |

|                                    |  |
|------------------------------------|--|
| Settled Sludge Volume (SSV)        | The volume occupied by activated sludge in a settlometer.  |
| Sewage                             | Used water of a community.   |
| Shock Load                         | The arrival at a plant of a waste which is toxic to organisms in sufficient quantity or strength to cause operating problems. Organic or hydraulic overloads can also cause shock load.  |
| Sludge Blanket                     | The distance under the surface of the final clarifier the settled sludge is lying.   |
| Sludge Bulking                     | When the weight of the activated sludge floc becomes lighter than water, the sludge will float out of the final clarifier. Bulking sludge will have a very disagreeable odor, be light gray in color and have a very high SVI. This condition is caused by the plant being out of balance or by some toxic material in the sewage. |
| Sludge Concentration Curves        | Plots of the SSC data calculated from the settlometer test data.   |
| Sludge Cycle                       | The length of time takes for bacteria to make one pass through the aeration basin and clarifier before being returned to aeration.   |
| Sludge Density Index (SDI)         | The reciprocal of the sludge volume index multiplied by 100 (that is, $1/\text{SVI} \times 100$ ).   |
| Settled Sludge Concentration (SSC) | The concentration of settled sludge based on the volume occupied in the settlometer.   |
| Sludge Digestion                   | A process by which the volatile organic in sludge is gasified, liquefied, mineralized, converted to a more stable form by anaerobic or aerobic organisms.  |
| Sludge Loading                     | A ratio of pounds of organic matter in the primary effluent to the pounds of MLSS.   |

|                             |   |
|-----------------------------|---|
| Sludge Volume Index (SVI)   | The volume in milliliters occupied by one gram of activated sludge after 30 minutes of settling. This is used as a measurement of sludge quality.   |
| Sludge Settling Curves      | Plots of the SSV data generated from the settlometer test.  |
| Sludge Residence Time (SRT) | A term expressing the length of time bacteria spend in the aeration tank.   |
| Solids Inventory            | The pounds of mixed liquor suspended solids in the aeration tank and secondary clarifier.   |
| Solids Loading              | The weight or mass of solids applied to a treatment process per unit time.  |
| Solids Retention Time (SRT) | The average residence time of suspended solids in the aeration tank; equal to the total weight of suspended solids in the aeration tank divided by the total weight of suspended solids leaving the system per unit time.   |
| Solids Washout              | The removal of sludge solids in the effluent from the secondary clarifier of an activated sludge plant because of excessive turbulence and/or a sludge buildup.   |
| Sparger                     | The air distribution device used with mixers for aeration of the mixed liquor in the hi-rate activated sludge process.  |
| Step Aeration               | A variation of the conventional activated sludge process where settled sewage is introduced into the aerator at several different points along the aerator. This is done to improve the mixing and to minimize shock loads. |
| Straggler Floc              | In activated sludge, flow particles 1/4" or larger extending throughout the clarifier, associated with low mixed liquor suspended solids.   |

|                              |  |
|------------------------------|--|
| Substrate                    | The substance to which microorganisms in suspension adhere.  |
| Suspended Solids (SS)        | The material that is collected on a filter as measured in the laboratory.  |
| Synthesis                    | The creation of new material from elementary building blocks.  |
| Tapered Aeration             | An aeration method whereby the quantity of air added varies along the aeration basin with a maximum at the head end and a minimum at the outlet end. |
| Thermophilic                 | The temperature range most conducive to maintenance of optimum digestion by thermophilic bacteria, generally accepted as between 120° and 135°F.     |
| Total Solids                 | The solids in water that included suspended solids (filterable) and dissolved solids (non-filterable).   |
| Toxic                        | Conditions or substances which inhibit the activity of or kill organisms.  |
| Ultimate Compaction          | Expression used to described when sludge settling has stopped in the clarifier and the sludge concentration is at its maximum.                       |
| Volatile Solids              | The quantity of solids lost on ignition at 600°C.  |
| Wastewater                   | The used water and solids that flow into a treatment plant.  |
| Waste Activated Sludge (WAS) | The excess portion of the settled activated sludge removed from the process.   |
| Waste Sludge Flow (WSF)      | The rate at which sludge is wasted from the activated sludge system.   |

APPENDIX A  
LABORATORY SUMMARY

| PARAMETER  | HOLDING/SAMPING                               | PRETREATMENT   | APPARATUS   | PROCEDURE  | COMMENTS   | CALCULATIONS   |
|--|---|--|---|--|--|--|
| Biochemical Oxygen Demand (BOD), mg/L<br>[See Appendix W]                          | 24 hr, refrigerate at 4°C, grab or composite  | -pH 6.4 to 7.5<br>-dechlorinate<br>-temperature 20°C           | -300 mL BOD incubation bottles<br>-Incubator @ 20°C                                 | 5 days in the dark @ 20°C  | -dilution water depletion must not exceed 0.2 mg/L                               | $\frac{(DO_{initial} - DO_{final}) \times 300}{\text{sample volume}}$<br>DO depletion in sample bottles must be at least 2 mg/L and final DO must be at least 1.0 mg/L |
| Total Suspended Solids (TSS), mg/L   | 7 days, refrigerate at 4°C, grab or composite | - well mixed sample  | -glass fiber filter (Whatman 934AM, Millipore AP40, Gelman A/E)<br>-Imhoff cone     | Dry in oven @ 105°C ± 2°C until constant weight is achieved  | -insert filter paper wrinkled side up.   | $\frac{(\text{Wt. of filter \& sample} - \text{wt of filter})}{\text{sample volume (mL)}}$   |
| Settleable Solids mL/L   | 48 hr, refrigerate at 4°C, grab               |  |   | Settle for 45 min., stir gently, settle for 15 min. longer   |  | Direct read  |
| Fecal Coliform colonies/100mL  | 30 hr, refrigerate @ 4°C, grab                | -dechlorinate if necessary                                     | -filter paper<br>-filter funnel<br>-nutrient broth<br>-culture dishes<br>-incubator | Incubate at 35°C ± 0.5°C for 22 to 24 hours  | 20 to 60 colony range desired  | $\frac{(\text{colonies counted}) \times 100}{\text{sample volume (mL)}}$   |
| <i>E. coli</i> Colonies/100 mL   | 30 hr, refrigerate @ 4°C, grab                | -dechlorinate if necessary                                     | -filter paper<br>-filter funnel<br>-nutrient broth<br>-culture dishes<br>-incubator | Incubate at 35°C for 2 hrs then at 44.5°C for 22 hrs ± 2 hrs   | 20 to 80 colony range desired  | $\frac{(\text{colonies counted}) \times 100}{\text{sample volume (mL)}}$   |
| pH   | Analysis must be done immediately, grab       |  | -pH meter   | Calibrate pH meter against at least 2 known buffers that bracket the expected pH value                 | -meter must be accurate to ±0.1 units<br>-sample must fall between buffer values | Direct read  |
| Total Chlorine Residual (TRC), mg/L  | Analysis must be done immediately, grab       |  | -spectrophotometer or colorimeter<br>-TRC reagents                                  | Add reagent to sample, mix well, let stand 3-5 min., read results                                      |  | Direct read  |
| Specific Oxygen Uptake Rate (SOUR), (mg/g)/hr<br>[See Appendix H]                  | Analysis must be done immediately, grab       | -adjust temp to ~20°C<br>-oxygenate sample by vigorous shaking | -DO meter/ stirrer probe & temp<br>-stopwatch<br>-BOD bottle                        | Fill BOD bottle to overflowing with sample. Insert probe and activate stirrer                          | After DO stabilizes, read DO level every minute for 15 min or until DO < 1.0     | $\frac{DO_{\text{Uptake rate}}}{\text{MLVSS (g/L)}} \times \frac{60 \text{ min}}{\text{hr}}$   |
| Settled Sludge Volume (SSV) mL/L and Sludge Volume Index (SVI)<br>[See Appendix G] | Analysis must be done immediately, grab       |  | -Mallory settle-ometer or equiv w/ stirrer<br>-thermometer                          | Mix sample w/ stirrer, pull strier gently from settleometer, record settled sludge volume every 5 min. | SVI Calculated from SSV at 30 minutes and MLSS concentration                     | $\frac{\text{SSV at 30 min} \times 1000}{\text{MVSS (mg/L)}}$  |

## APPENDIX B

### DESIGN AND OPERATING PARAMETERS

| PARAMETER   |                                  |                               |                      | CONTACT - STABILIZATION |                | STEP<br>AERATION | FORMULA  |
|---|----------------------------------|-------------------------------|----------------------|-------------------------|----------------|------------------|--|
|   | CONVENTIONAL<br>ACTIVATED SLUDGE | HIGH RATE<br>ACTIVATED SLUDGE | EXTENDED<br>AERATION | CONTACT                 | REAERATION     |                  |  |
| AERATION DETENTION<br>TIME (hrs)                        | 4 - 8                            | 2 - 4                         | 18 - 30              | 0.5 - 1.0               | 3 - 6          | 3 - 6            | $\frac{(\text{TANK VOLUME, cu ft})(7.5 \text{ gal/cu ft})(24 \text{ hr/day})}{\text{FLOW, gal/day}}$   |
| AERATION TANK<br>ORGANIC LOADING<br>(lb BOD/1000 cu ft) | 25 - 50                          | 50 - 100                      | 5 - 15               |                         | 30 - 70        | 30 - 70          | $\frac{(\text{PRIMARY EFFLUENT BOD, mg/L})(\text{FLOW, mgd})(8.34 \text{ lb/gal})}{\text{VOLUME AERATION TANK, 1000 cu ft}}$   |
| MIXED LIQUOR<br>SUSPENDED SOLIDS<br>(mg/L)              | 1,500 - 3,000                    | 1,200 - 2,500                 | 2,000 - 6,000        | 1,000 - 2,500           | 4,000 - 10,000 | 2,000 - 3,500    | $\frac{(\text{DRY WEIGHT OF SAMPLE, g})(1000 \text{ mg/g})(1000 \text{ ml/L})}{\text{SAMPLE SIZE, mL}}$  |
| FOOD-to-MICROORGANISM<br>RATIO (F:M)                    | 0.2 - 0.5                        | 0.5 - 1:0                     | 0.02 - 0.10          |                         | 0.2 - 0.6      | 0.2 - 0.5        | $\frac{(\text{PRIMARY EFF BOD, mg/L})(\text{FLOW, mgd})(8.34 \text{ Lb/gal})}{(\text{MLVSS, mg/L})(\text{AERATION TANK VOLUME, mg})(8.34 \text{ lb/gal})}$                       |
| SLUDGE AGE - SRT<br>(days)                              | 4 - 10                           | 2 - 4                         | 20 - 40              |                         | 4 - 16         | 4 - 10           | $\frac{(\text{MLSS, mg/L})(\text{AERATION TANK VOLUME, mg})(8.34 \text{ lb/gal})}{(\text{RAS, mg/L})(\text{WAS, mgd})(8.34) + (\text{Effluent TSS, mg/L})(\text{Q, mgd})(8.34)}$ |
| AIR REQUIREMENT<br>(cu ft/lb BOD REMOVED)               | 750 - 1,200                      | 650 - 850                     | 2,000 - 3,500        | 750 - 1,200             |                | 600 - 850        | $\frac{\text{AIR APPLIED, cu ft}}{\text{PRIMARY EFFLUENT. BOD, mg/L}(\text{FLOW, mgd})(8.34 \text{ lb/gal})}$  |
| OXYGEN REQUIREMENT<br>(lb/lb BOD, REMOVED)              | 0.8 - 1.1                        | 0.7 - 0.9                     | 1.4 - 1.6            |                         | 0.8 - 1.2      | 0.6 - 0.8        | $\frac{\text{OXYGEN APPLIED lbs}}{(\text{PRIMARY EFFLUENT BOD, mg/L})(\text{FLOW, mgd})(8.34 \text{ lb/gal})}$   |
| RESPIRATION RATE -<br>OUR (mg/hr/g MLSS)                | 7 - 15                           | 15 - 25                       | 3 - 8                | 20 - 30                 | 10 - 30        | 8 - 20           | $\frac{(\text{OUR, mg/L/hr})(1,000 \text{ mg/g})}{\text{MLSS, mg/L}}$  |
| SOLIDS AECUMULATON<br>RATE (lb/lb BOD REMOVED)          | 0.7 - 0.9                        | 0.8 • 1.0                     | 0.65 - 0.8           |                         | 0.9-1.1        | 0.7 - 0.9        | $\frac{(\text{RAS, mg/L})(\text{WAS, mgd})(8.34) + (\text{EFF, mg/L})(\text{Q, mgd})(8.34)}{(\text{PRIMARY EFF - FINAL EFF BOD, mg/L})(\text{FLOW, mgd})(8.34)}$                 |
| SLUDGE VOLUME INDEX -<br>SVI (ml/g)                     | 50 • 150                         | 50 - 150                      | 25 - 110,            |                         | 50 - 150       | 50 - 150         | $\frac{(\text{30-MINUTE -SETTLED SLUDGE VOLUME, mL})(1000)}{\text{MLSS, mg/L}}$  |
| RETURN SLUDGE<br>CONCENTRATION (mg/L)                   | , 6,000                          | 6,000                         | 7,500                |                         | 8,000          | 6,000            | $\frac{(\text{DRY WT OF SAMPLE, g})(1000 \text{ mg/g})(1000 \text{ mL/L})}{\text{SAMPLE SIZE, mL}}$  |
| RETURN SLUDGE<br>(% OF INFLUENT)                        | 25 - 75                          | 25 - 100                      | -50 - zoo            |                         | 50 - 125       | 25 - 75          | $\frac{(\text{RETURN ACTIVATED SULDGE FLOW, mgd})(100)}{-(\text{INFLUENT FLOW, mgd})}$   |
| CLARIFIER OVERFLOW<br>RATE (gal/sq ft/day)              |                                  |                               |                      |                         |                |                  | $\frac{\text{FLOW, gal/day}}{(\text{CKLARIFIER SURFACE AREA, sq ft})}$   |
| PRIMARY   |                                  |                               | 800-1,200            |                         |                |                  |  |
| SECOIARY  | 400 - 800                        |                               | 200 - 400            |                         | 400 - 800      |                  |  |
| PRIMARY CLARIFIER<br>DETENT ION TI ME C(hrs)            |                                  |                               | 1 - 2                |                         |                |                  |  |
| CLARIFIER DEPTH (ft)                                    |                                  |                               |                      |                         |                |                  | $\frac{(\text{TANK VOLUME, cu ft})(7.5 \text{ gal/cu ft})(24 \text{ hr/day})}{\text{FLOW, gal/day}}$   |
| PR IMARY  |                                  |                               | 10 - 12              |                         |                |                  |  |
| SECONDARY   |                                  |                               | 1 - 15               |                         |                |                  |  |
| CLARIFIER WEIR<br>LOADING<br>(gal/ft/day)               |                                  |                               | 20,000               |                         |                |                  | $\frac{\text{FLOW, gal/day}}{(\text{LENGTH OF EFFLUEN WEIR, ft})}$   |
| SOLIDS LOADING<br>(lb/day/sq ft)                        | 20 - 30                          | 20 - 30                       | 5 - 25               |                         | 20 - 30        | 20 - 30          | $\frac{(\text{FLOW, mgd} + \text{RAS, mgd})(\text{MLSS, mg/L})(8.34)}{(\text{CLARIFIER SURFACE AREA, sq ft})}$   |

Appendix C

## **The Microbiology of Activated Sludge**

From <http://www.dnr.state.wi.us/org/water/wm/ww/tech/biol.htm>

And

## **Process Control**

From: <http://dnr.wi.gov/org/water/wm/ww/tech/process.htm>

# The Microbiology of Activated Sludge

Activated sludge can be defined as "a mixture of microorganisms which contact and digest biodegradable materials (food) from wastewater."

- Activated sludge is *microorganisms*.
- The Activated sludge process is a *biological process*.
- To properly control the activated sludge process, you must properly control the growth of microorganism. This involves controlling the items which may affect those microorganisms.

Additional technical assistance with wastewater treatment plant operations is available from the DNR. Contact Jack Saltes in Madison at (608) 264-6045. For additional help from the DNR, you might also try the Laboratory Certification Program at <http://www.dnr.state.wi.us/org/es/science/lc/>

---

## Bacteria

- Make up about 95% of the activated sludge biomass.
- These single celled organisms grow in the wastewater by consuming (eating) biodegradable materials such as proteins, carbohydrates, fats and many other compounds.

## The Role of Enzymes

Enzymes are compounds that are made by living organisms. Their purpose is to help biochemical reactions to occur. Almost all biochemical reactions require the presence of enzymes to cause the reaction to occur.

Enzymes help bacteria in the process of breaking down nutrients, and in rebuilding broken down nutrients into the new compounds that they require for growth and reproduction.

Enzymes only do what they are supposed to when environmental conditions are right. If the conditions are not right the enzymes will not function properly, thus, the bacteria will not function properly, and they will not survive. If conditions are right the bacteria will live and prosper.

## Growth Characteristics

When there is plenty of food available, bacteria use the food mostly for growth and some for energy.

- A growing bacterium has flagella (hair-like structures on the outside of the cell) which makes it motile, able to move in search of food.

- A bacterium reproduces into two bacteria. The cell splits into two smaller cells and this process occurs over and over again.

When there is very little food available, the bacteria use the limited food to produce energy and to maintain the cell. Very little is available for growth so less reproduction occurs.

- With little food available, and in an attempt to conserve energy, the bacterium loses its flagella and thus, its motility.
- The waste products start to form a thick slime layer outside the cell wall, making the cells stick together.

The growth characteristics of bacteria are better understood by studying the growth curve.

- *Lag-phase* During this phase bacteria become acclimated to their new surroundings. They are digesting food, developing enzymes and other things required for growth.
- *Accelerated Growth-phase* The bacteria are growing as fast as they can, since there is an excess of food. The cells are mostly dispersed, not sticking together.
- *Declining Growth-phase* Reproduction slows down because there is not an excess of food. A lot of food has been eaten and there are now a large number of bacteria to compete for remaining food, so the bacteria do not have enough remaining food to keep the growth rate at a maximum.
- *Stationary-phase* The number of bacteria is the highest possible, but not much food is left, so the bacteria cannot increase in number. There is some reproduction, but some cells are also dying, so the number of bacteria remain relatively constant. The bacteria have now lost their flagella and have a sticky substance covering the outside of the cell, allowing them to agglomerate into floc. In fact, the floc get big enough that if aeration and mixing were stopped, the floc could settle to the bottom.
- *Death-phase* The death rate increases with very little if any growth occurring. Therefore, the total number of living bacteria keeps reducing. The bacteria are just trying to keep alive.

### **F:M (Food to Microorganism ratio)**

We measure the amount of biodegradable matter the bacteria use for food by measuring the amount of BOD (biochemical oxygen demand) or COD (chemical oxygen demand) in the influent to the aeration basin. We estimate the weight of microorganisms in the mixed liquor by measuring the amount of volatile suspended solids (VSS) in the activated sludge. We use this information to form a relationship called food to microorganism ratio (F/M ratio). The F/M ratio tells us something about growth and cell condition. If the F/M ratio is high, the bugs normally grow quite rapidly (because this means there is a lot of "food" available in comparison to the amount of microorganism); if the F/M ratio is low, the bug normally grow very slowly (because little food is available for growth).

## **The Use of Oxygen**

Microorganisms need oxygen to live. Oxygen use can be used to determine the activity of the organisms.

- Actively growing organisms are rapidly metabolizing the food, so they use oxygen at a rapid rate.
- We measure the rate at which oxygen is used by a test called the Oxygen Uptake Rate (OUR), or the Respiration Rate. It is measured in mg O<sub>2</sub>/hr/gm of MLSS.
- Normally a higher uptake rate is associated with high F/M ratios and younger sludges and a lower uptake rate is associated with lower F/M and older sludges. So, if you want a higher uptake rate, more sludge should be wasted. Less should be wasted if you want a lower F/M ratio.

## **The Formation of Floc**

As bacteria begin growing, they generally develop into small chains or clumps. They are very active and motile and it is difficult for them to settle. They have not yet developed the slime layer which aids in their sticking together. So, when mixing occurs, the small chains or clumps are broken up and the bugs are dispersed, and they will not flocculate or settle.

As the sludge is allowed to age, the bugs lose their motility and accumulate more slime. Then the clumps and chains are better able to stick together. The clumps grow bigger and bigger until they form a floc. If the organisms are allowed to develop properly, under the right conditions, the floc gets large and compact and begins to settle. The mixing in the aeration tank tends to keep the floc small since, even though the bugs are sticky, the bond formed holding the organisms together is not very strong. This is good because it allows the cells, food, and oxygen to contact each other.

## **Dissolved Oxygen**

Oxygen is required by these bugs to metabolize food for cell maintenance and growth. Although the bugs need oxygen, some bugs can get along with less oxygen than others.

Each bug must have a concentration of dissolved oxygen of at least from 0.1-0.3 mg/L to function properly. So, it is important to maintain about 2 mg/L of D.O. in the activated sludge so that the bacteria that are contained in the floc can get oxygen. If the DO is less than 2 mg/L, the bugs on the outside of the floc use the DO before it can get to the center of the floc. If this happens, the bugs in the center may die causing the floc to break up.

## **The Effects of Mixing**

Mixing is required to bring organisms, oxygen, and nutrients together, and to remove metabolic waste products. If there is not enough mixing, proper treatment will not take place because of lack of contact between the bugs, their food and oxygen. If too much mixing is provided, it can cause break up of floc or formation of unstable floc particles.

## **The Effects of pH**

The enzymes which regulate many of the biochemical reaction in bacteria are very pH dependent. The optimum pH should be between 7.0 and 7.5 for the proper activated sludge microorganisms to dominate.

## **The Effects of Temperature**

Biochemical reactions are very temperature dependent. Lower temperatures cause such reactions to be much slower. Thus, more bugs are required to do the same job during the winter than in the summer.

## **The Effects of Nutrients**

Microorganisms require certain nutrients for growth. The basic nutrients of abundance in normal raw sewage are carbon (C), nitrogen (N), phosphorus (P), with the ratio of C:N:P ratio approximately equal to 100:10:1. In addition to C, N, and P, trace amounts of sodium (Na), Potassium (K), magnesium (Mg), iron (Fe), and many others are required. In normal municipal sewage, most of these nutrients are provided.

Most problems with nutrient deficiency occur when there is a lot of industrial wastes present. When proper nutrients are not available, the metabolism fails and a kind of bacterial fat (slime) will begin to accumulate around the cell. The cell slows down in activity because it cannot produce enough enzymes and because needed nutrients cannot penetrate the slime layer as they should. The sludge will not settle and BOD removal slows down.

## **Protozoa & Rotifers**

The presence of particular types of protozoans is related to effluent quality and plant performance. Protozoans play secondary but important role in purification of aerobic wastewater.

The protozoans in the activated sludge treatment process fall into four major classes: amoebae, flagellates, and ciliates (free-swimming, crawling, and stalked).

- Amoebae

Amoebae are the most primitive, single-celled protozoans. They move by false feet. They are frequently present in raw influent, and their presence is short in the aeration basin. Amoebae can only multiply when there is an abundance of nutrients in the aeration tank. They move very slowly and it is difficult for them to compete for the limited amount of food available. They are only dominant in the aeration basin for a short time.

Amoebae feed on small organic particulates. When amoebae are present in large numbers in the aeration basin this usually indicates that there has been some sort of shock loading to the plant (there must be a lot of food available). Their presence may

also indicate that there is a low D.O. environment in the aeration basin, because they can tolerate very low amounts of D.O.

- Flagellates

Most flagellates absorb dissolved nutrients. They appear soon after amoebae begin to disappear and while there is still high concentrations of soluble food. Flagellates and bacteria both feed on organic nutrients in the sewage so as the nutrient level declines they have difficulty out-competing the bacteria for soluble food so, their numbers begin to decrease.

If large amounts of flagellates are present in the later stages of the activated sludge development this usually indicates that the wastewater still contains a large amount of soluble organic nutrients.

- Ciliates

Ciliates feed on bacteria, not on dissolved organics. While bacteria and flagellates compete for dissolved nutrients, ciliates compete with other ciliates and rotifers for bacteria. The presence of ciliates indicate a good sludge, because they dominate after the floc has been formed and after most of the organic nutrients have been removed.

- Free-swimming ciliates - These ciliates appear as flagellates begin to disappear. As the bacterial population increases, a lot of dispersed bacteria is available for feeding and as a lightly dispersed floc appears, free-swimming ciliates begin to dominate and feed on the increased numbers of bacteria.
- Crawling ciliates - As floc particles enlarge and stabilize, crawling ciliates graze on floc particles. Crawling ciliates out compete free-swimming ciliates for food because they can find food within the floc.
- Stalked ciliates - Stalked ciliates appear in the mature sludge. Within the mature sludge the crawling and stalked ciliates compete for dominance.

## **Factors Influencing Protozoa**

### **Temperature**

Most protozoans can survive and reproduce in a temperature range at which activated sludge processes are carried out. They grow best in ambient temperatures (15-25 oC).

### **pH**

Protozoans are more sensitive to pH than floc-forming bacteria. They have an optimum pH range of 7.2 - 7.4 and a tolerance range of 6.0 - 8.0.

### **Dissolved Oxygen**

Like bacteria, protozoan must have oxygen to survive. Thus lack of DO will severely limit both the kind and number of protozoans.

## **Nutrition**

Most municipal wastewater treatment plants, however dilute, contains sufficient nutrients to support most of the protozoan associated with wastewater.

## **Rotifers**

Rotifers are rarely found in large numbers in wastewater treatment processes. The principal role of rotifers is the removal of bacteria and the development of floc. Rotifers contribute to the removal of effluent turbidity by removing non-flocculated bacteria. Mucous secreted by rotifers at either the mouth opening or the foot aids in floc formation. Rotifers require a longer time to become established in the treatment process. Rotifers indicate increasing stabilization of organic wastes.

## **Introduction to Filament Identification**

### **Filament Identification**

In order to identify many of the following filament characteristics, the mixed liquor must be examined under 100X using immersion oil. It is difficult to see many of these characteristics under lower magnifications.

### **Filament Shape and Length**

Filaments may be long, short, smoothly curved, coiled, irregularly bent, straight, or bundled.

### **Individual Cell Shape**

Filamentous bacteria are made up of a chain of cells. The shape of the individual cells is a characteristic that can help us to identify the different filamentous bacterial types. Cell shape may be round, square, rectangular, oval, or discoid.

### **Cell Septa**

The cell septa is the "line" which separates each individual cell which makes up the bacterial filament.

The septa are clearly seen in some filaments and is very difficult to see in others. Some septa are "indented" and some are not. Indentations and the ability to clearly see the cell septa are other characteristics which can help us to identify the different filamentous bacteria.

### **Motility**

Motility is the ability of an organism to produce motion or to move.

*Beggiatoa spp* is only one filamentous bacterium found in activated sludge that is motile.

## **Intercellular Granules**

Some filaments store by-products as intercellular granules (mostly sulfur granules).

Sulfur granules can be seen very clearly under phase contrast and are found usually in septic wastes. Sulfur granules are commonly found in *Beggiatoa*, *Thiothrix* and type 021N.

## **Branching**

Branching may be "true" or "false". If a filament has true branching the intercellular fluids will flow freely throughout all the branches of the filament. Intercellular fluids cannot flow through false branches. In false branching the filament are simply attached to each other simulating a branch.

There are only two filaments which exhibit branching; one has true branching and the other false. *Nocardia spp* has true branching and *Sphaerotilus natans* exhibits false branching.

## **Sheath**

The cells of some filamentous organisms are contained in a tight fitting sheath. The easiest way to detect a sheath is to look for "missing spaces" between the cells.

Some filaments which have a sheath are *Haliscomenobacter hydrosis*, *Sphaerotilus natans*, type 1701, type 0041, and type 0675.

## **Attached Growth**

Some filaments have bacterial cells attached along the side, perpendicular to the filament.

There are three filaments on which this commonly occurs. Type 0041, type 0675, and type 1701.

# Process Control

Microscopic examinations of activated sludge can help to assess the condition of the biomass in an aeration basin and the settleability of the sludge. It can also aid in the identification of filamentous bacteria that may cause problems in wastewater treatment plants.

Additional technical assistance with wastewater treatment plant operations is available from the DNR. Contact Jack Saltes in Madison at (608) 264-8954. For additional help from the DNR, you might also try the Laboratory Certification Home Page at <http://dnr.wi.gov/org/es/science/lc/>.

---

## Floc Particles: Sizes and Shapes

When floc particles first develop in the activated sludge process, that is, at a relatively young sludge age, the particles are small and spherical. Because filamentous organisms do not develop or elongate at relatively young sludge ages, the floc-forming bacteria can only "stick" or flocculate to each other in order to withstand shearing action.

Bacterial flocculation and the absence of filamentous organisms result in spherical floc particles.

As the sludge age increases and the short filamentous organisms within the floc particles begin to elongate, the floc-forming bacteria now flocculate along the lengths of the filamentous organisms.

These organisms provide increased resistance to shearing action and permit a significant increase in the number of floc-forming bacteria in the floc particles. The presence of long filamentous organisms results in a change in the size and shape of floc particles.

The floc particles increase in size to medium and large and change from spherical to irregular.

## Factors Interrupting Floc Formation

- Young sludge age (< 3 days)
- Toxicity (heavy metals etc.)
- Slug discharge
- Lack of active and abundant ciliated protozoan population
- Excessive shearing
- Excessive surfactant

## **Dispersed Growth**

Dispersed growth is a population of bacteria that is suspended in the liquid portion of the mixed liquor. These bacteria are still growing rapidly and have not begun to flocculate. Most dispersed growth is bacterial.

Only a little dispersed growth should be present in a properly operating activated sludge process.

Ciliated protozoa play an important role in the removal of dispersed growth. Dispersed growth is also removed from the bulk medium by its adsorption to the surface of floc particles.

A significant amount of dispersed growth is present at the start-up of an activated sludge process. A lot of food is available, and the bacteria are very active and are multiplying rapidly. The presence of significant or excessive dispersed growth within the mixed liquor can also be due to the interruption of proper floc formation.

For more information on the interruption of floc formation see, [Floc Particles, Sizes & Shapes](#).

## **Slime Bulking**

Often in industrial and municipal activated sludge processes a nutrient deficiency may occur. The nutrients that are usually deficient in these processes are either nitrogen or phosphorus. This deficiency results in the production of nutrient deficient floc particles, loss of settleability, and, possibly billowy white or greasy gray foam on the surface of the aeration tank.

During a nutrient deficiency, the bacteria within the floc particles remove soluble BOD from the wastewater. However, when nitrogen or phosphorus is deficient, the soluble BOD is not degraded but it is stored within the floc particles as an exocellular polymer-like material. This slimy material interferes with settling and may cause foam upon aeration.

## **Operational Considerations**

The solution usually involves addition of the limiting nutrient, such as ammonia to provide nitrogen, or phosphoric acid to provide phosphorus. There is usually enough nutrient if the ammonia plus nitrate in filtered (0.45  $\mu$ m) effluent is greater than 1 mg/L and the soluble orthophosphate is greater than 0.5 mg/L. However, in cases where easily degradable, soluble BOD is available, higher N and P concentrations may be necessary.

## Toxicity

Toxicity assessment is one of the most valuable applications of microscopic observation of microorganisms in activate sludge. The higher life forms, particularly the ciliates and the rotifers, are generally the first to be impacted by toxic materials and may serve in essence as an in-plant biomonitoring test for toxicants or other adverse stresses.

The first noticeable sign of toxicity or stress is usually the slowing or stopping of cilia movement for these organisms and small flagellates and ciliates begin to predominate. This is an indication of the break up of the floc and an over abundance of free bacteria used by these organism as a food source.

Indications of toxicity upset include:

- Loss of the higher life forms in the activated sludge (these are the most toxic sensitive microbial components).
- A dispersed activated sludge biomass with poor floc formation and pin floc.
- Unusually low oxygen use, caused by poor biomass growth.
- Poor BOD removal.

What can you expect to see under the microscope if toxic conditions exist?

- There will be a sudden increase in flagellates. This is sometimes called a flagellate "bloom".
- The of protozoa and higher life forms will begin to die off
- Break-up of floc, sometimes accompanied by foaming
- Loss of BOD removal
- Filamentous bulking upon process recovery. Filamentous bacteria are very often the first to recover after a toxic upset.

Toxic wastes generally do not favor filaments directly (except in the case of H<sub>2</sub>S), rather upset conditions allow filaments to grow.

Microscopic examination of activated sludge can diagnose toxicity, however, this is usually "after the fact". A better method of toxicity detection is the use of oxygen uptake rate testing to detect toxicity early and to find the source.

## Filamentous Bulking and Foaming

| Filamentous Organism   | Factors Promoting Rapid Growth         |
|--|--|
| <i>Haliscomenobacter hydrosis</i> , <i>Sphaerotilus natans</i> , type 1701   | Low D.O.                               |
| <i>Haliscomenobacter hydrosis</i> , <i>Microthrix parvicella</i> , <i>Nocardia spp.</i> , type 021N, type 0041, type 0092, type 0581, type 0675, type 0803 and type 0961 | Low F/M                                |
| <i>Sphaerotilus natans</i> , <i>Thiothrix spp.</i> fungi, type 0675 and type 021N  | Low Nutrients (nitrogen or phosphorus) |
| <i>Nocardia spp</i> fungi  | Low pH                                 |
| Type 0041, type 0092, and <i>Microthrix parvicella</i>   | Low Organic Load                       |
| <i>Beggiatoa spp</i> , <i>Thiothrix spp</i> and type 021N  | Septic Wastewater/Sulfides             |

## Significant Foam Producing Filaments

| Foam Producing Filaments     | Factors Influencing Their Growth                                  |
|------------------------------|---|
| <i>Microthrix parvicella</i> | Low F:M and high wastewater grease and fat, colder temperatures   |
| <i>Nocardia spp</i>          | Longer MCRT, excess grease, oils and fats and warmer temperatures |
| type 1863                    | Low D.O., excess grease and fat, and low pH                       |

To determine if aeration tank or clarifier foam is due to the growth of foam-producing filamentous organisms, a sample of fresh foam should be spread thinly and evenly over a clean microscope slide, and the slide stained by Gram staining.

*Microthrix parvicella* and *Nocardia spp* each stain Gram positive (staining purple or dark blue). *Microthrix* is a long thin filament while *Nocardia* is a short branched filament. So, if you have foam and slide of mixed liquor stains Gram positive, you can easily determine which filament is responsible.

Type 1863 stains Gram negative (staining pink). Type 1863 is a long filament which looks like a dashed line.

If the foam is not due to foam-producing filamentous organisms, it may be due to the presence of a nutrient deficiency. To determine if a nutrient deficiency is the cause of foam production, a representative sample of mixed liquor should be treated with India ink and examined under phase contrast microscopy for the presence of nutrient deficient floc particles.

## **ACTIVATED SLUDGE MICROBIOLOGY PROBLEMS AND THEIR CONTROL**

Michael Richard, Ph.D.  
Sear-Brown  
Fort Collins, CO

### **CONTENTS**

- I. Introduction
- II. Microbiology Problems and Their Causes
  - 1. Poor Floc Formation, Pin Floc and Dispersed Growth Problems
  - 2. Toxicity
  - 3. Nitrification and Denitrification Problems
  - 4. Nutrient Deficiency and Polysaccharide Bulking and Foaming
  - 5. Zoogloal Bulking and Foaming
  - 6. Filamentous Bulking
  - 7. Filamentous Foaming
- III. Practical Control Methods for Filamentous Bulking and Foaming
  - 1. Short Term Control Methods
    - a. Sludge Juggling
    - b. Polymer Addition
    - c. Chlorination
  - 2. Long Term Control Methods
    - a. Low Dissolved Oxygen Problems
    - b. Wastewater Septicity and Organic Acids
    - c. Low F/M Conditions and Selectors
    - d. Nutrient Deficiency
    - e. Foaming Control
- IV. Summary
- V. References and Additional Information

## **INTRODUCTION**

Many problems can develop in activated sludge operation that adversely affect effluent quality with origins in the engineering, hydraulic and microbiological components of the process. The real "heart" of the activated sludge system is the development and maintenance of a mixed microbial culture (activated sludge) that treats wastewater and which can be managed. One definition of a wastewater treatment plant operator is a "bug farmer", one who controls the aeration basin environment to favor good microbiology.

This paper will discuss the types of microbiological problems that can occur in activated sludge operation. These include dispersed (non-settleable) growth, pin floc problems, zoogloal bulking and foaming, polysaccharide ("slime") bulking and foaming, nitrification and denitrification problems, toxicity, and filamentous bulking and foaming. The best approach to troubleshooting the activated sludge process is based on microscopic examination and oxygen uptake rate (OUR) testing to determine the basic cause of the problem or upset and whether it is microbiological in nature. These methods are easy, fast and inexpensive compared to other approaches, and are generally understandable and accepted.

## **MICROBIOLOGY PROBLEMS AND THEIR CAUSES**

### **Poor Floc Formation, Pin Floc and Dispersed Growth Problems**

Basic floc formation, required for activated sludge operation due to the use of gravity clarifiers, is due to a growth form of many species of natural bacteria. Floc-forming species share the characteristic of the formation of an extracellular polysaccharide ("slime") layer, also termed a glycocalyx. This material, which consists of polysaccharide, protein and sometimes cellulose fibrils, "cements" the bacteria together to form a floc. Floc formation occurs at lower growth rates and at lower nutrient levels, essentially starvation or stationary growth conditions.

Floc-forming species may grow in a dispersed and non-settleable form if the growth rate is too fast. This latter condition, termed dispersed growth, occurs rarely in domestic waste activated sludge operation but occurs often in industrial waste treatment, generally due to high organic loading (high food to microorganism ratio (F/M) conditions). Here, no flocs develop and biomass settling does not occur, resulting in a very turbid effluent. The correct remedial action for a dispersed growth problem is a reduction in the F/M of the system, usually done by raising the MLSS concentration. Dispersed growth problems often occur after a toxicity or hydraulic washout event when the activated sludge biomass is low and high F/M conditions prevail.

Small, weak flocs can be formed in activated sludge that are easily sheared and subject to hydraulic surge flotation in the final clarifier leading to a turbid effluent. These small flocs, termed pin floc, consist only of floc-forming bacteria without a filament backbone and usually

are <50um in diameter. Pin floc occurs most commonly at starvation conditions -- a very low F/M and long sludge age. Chronic toxicity can also cause a pin floc condition.

Free floating filaments can, at times, cause a dispersed growth problem. Here, the cause is filament-specific and is the same as for filamentous bulking (discussed below).

## **Toxicity**

Toxic shocks can be a severe problem in activated sludge operation. In a recent study, toxicity upset was experienced by approximately 10% of 25 Colorado activated sludge plants examined during one year. Toxicity problems were found to be a larger problem in small communities compared to larger cities, due to the lack of dilution of toxic releases in small systems. Examples of toxicity events were the washing of cement or lime trucks to a manhole, dumping of congealed diesel fuel to the sewer system, and overload of small systems with septage (which contains a high amount of organic acids and sulfides which can be toxic).

Sulfide toxicity to activated sludge is more common than currently recognized. Sulfide may originate from outside the activated sludge system, from septic influent wastewater or from septage disposal, or it may originate "in-house", from anaerobic digester flows or from aeration basins or primary or final clarifiers with sludge build-up and anaerobic conditions. Hydrogen sulfide toxicity is highly pH dependent, due to the H<sub>2</sub>S form being the toxic agent and not HS<sup>-</sup>. The pK<sub>a</sub> for H<sub>2</sub>S is 7.0, indicating higher toxicity at a pH of 7 or less when H<sub>2</sub>S is predominant, and less toxicity as the pH increases above pH 7 and H<sub>2</sub>S dissociates. One mg/L of H<sub>2</sub>S reduces the activated sludge OUR by 50% at pH 7, and the H<sub>2</sub>S dose to give a 50% OUR reduction increases to 100 mg/L at pH values above pH 8. It is advised to add lime or other alkaline agent to the aeration basin to raise the pH to 7.5 or above if sulfide toxicity is occurring.

Toxicity can be diagnosed microscopically, often in the following sequence:

1. an initial flagellate "bloom";
2. subsequent complete die-off of protozoa and other higher life forms;
3. biomass deflocculation, often accompanied by foaming;
4. loss of BOD removal; and
5. filamentous bulking upon process recovery.

Toxic wastes generally do not favor filaments directly (except in the case of H<sub>2</sub>S); rather, upset conditions allow filaments to proliferate. For example, bulking by *Sphaerotilus natans* frequently follows a toxic upset due to a high F/M condition. Here the "true" F/M value may be many-fold that calculated based on total biomass present, due to low viability of the biomass.

While microscopic observations can diagnose toxicity after the fact, a better method is use of the OUR test to detect toxicity early.

The OUR of an activated sludge fed increasing amounts of a nontoxic waste will initially rise with increasing waste additions to the test bottle, followed by no further increase in OUR with even higher waste additions. In contrast, the OUR of an activated sludge fed a toxic waste may increase initially with increasing waste strength, but will decrease rather dramatically at waste additions above a toxicity threshold value. A useful definition of microbial "death" is when the fed OUR is less than the basal endogenous OUR.

The OUR test is simple (all that is required is as a BOD bottle and a dissolved oxygen probe) and usually takes less than two hours to perform. The normal OUR of the activated sludge must be known before hand, so run this test periodically to know what is normal for your plant.

### **Nitrification and Denitrification Problems**

Nitrification can create problems in activated sludge operation. Many plants experience an upset condition with dispersed growth and filamentous bulking every spring when warmer temperatures induce nitrification. Some plants experience a loss of chlorine disinfection during nitrification onset, due to a transient period (weeks) of nitrite build-up. Nitrite has a significant chlorine demand (one part nitrite consumes one part chlorine) while ammonia and nitrate do not.

A large problem in some plants is a low pH (to as low as  $\text{pH} = 6$ ) caused by extensive nitrification and low wastewater alkalinity. This often causes pin floc and high effluent turbidity. Some plants reduce aeration to reduce nitrification or add soda ash, lime or magnesium hydroxide as a source of alkalinity if this becomes a problem. The use of lower dissolved oxygen concentration (1.0 mg/L or less) to control nitrification is not without the risk of inducing filamentous bulking by low dissolved oxygen filaments.

Another problem caused by nitrification is denitrification. Here, bacteria common in the activated sludge floc respire using nitrate in place of free oxygen when it is lacking and release nitrogen gas as a by-product. This gas is only slightly soluble in water and small nitrogen gas bubbles form in the activated sludge and cause sludge blanket flotation in the final clarifier. An indication of the occurrence of denitrification can be obtained by holding the sludge in the settling test jar for several hours. If the sludge rises ("pops") within 2 hours or less, denitrification problems may be occurring. Denitrification problems are more prevalent during the warmer times of the year and can be more severe if a filamentous sludge is present, due to more extensive entrapment of the nitrogen gas bubbles by a filamentous sludge.

Control of denitrification is either by control of nitrification (reduced sludge age or reduced aeration); or by reducing denitrification by removing the sludge faster from the final clarifier (increased RAS rates) or by increasing the dissolved oxygen concentration in the final clarifier. This can be done by increasing the aeration basin dissolved oxygen concentration especially at the clarifier end of the aeration basin. One method useful in severe cases is the addition of hydrogen peroxide as an oxygen source directly to the center well of the final clarifier.

Nitrification and denitrification problems can be particularly troublesome in industrial waste systems where ammonia is supplemented. Here, inorganic nitrogen (ammonia or nitrate) must be

present in the aeration basin at all times to allow proper treatment and to avoid filamentous or slime bulking but must be kept below approximately 5 mg/L to avoid nitrification-denitrification problems (low pH and floating sludge). The common practice of batch addition of nutrients to the aeration basin often leads to denitrification problems due to periods of high nitrate concentration (above 5 mg/L).

A number of industries, particularly papermills, have experienced a frothy, floating sludge in the aeration basin. This can lead to a significant amount of the sludge inventory in the foam, compromising process control. This problem occurs in systems with a high front-end organic loading and a long hydraulic detention time (2 days or more). Nitrification and denitrification occur at the back end of the system due to endogenous conditions there and the release of ammonia from the biomass. Nitrification and denitrification often occur together within the floc, with no finding of free nitrate when examined.

### **Nutrient Deficiency and Polysaccharide Bulking and Foaming**

Nitrogen and phosphorus can be growth limiting if not present in sufficient amounts in the influent wastewater, a problem with industrial wastes and not domestic wastes. In general, a BOD<sub>5</sub>:N:P weight ratio in the wastewater of 100:5:1 is needed for complete BOD removal. Other nutrients such as iron or sulfur have been reported as limiting to activated sludge, but this is not common.

Extracellular polysaccharide is produced by all activated sludge bacteria and is, in part, responsible for floc formation. Overproduction of this polysaccharide can occur at nutrient deficiency (and also oxygen deficiency or high F/M) which builds up in the sludge (it is poorly degraded) and leads to poor sludge settling, termed "slime bulking", and to problems in sludge dewatering. Normal activated sludge contains from 10 to 20% polysaccharide on a dry weight basis with the higher polysaccharide content occurring at younger sludge ages. Sludges with polysaccharide content above 20% may have settling and dewatering problems (values to 90% have been observed with some nutrient deficient industrial waste sludges).

Signs of nutrient deficiency include: filamentous bulking; a viscous activated sludge that exhibits significant exopolysaccharide ("slime") when "stained" with India ink; and foam on the aeration basin that contains polysaccharide (which has surface active properties). One check for nutrient deficiency is to be sure that some ammonia or nitrate and ortho-phosphate remain in the effluent at all times. The recommended effluent total inorganic nitrogen (ammonia plus nitrate) and ortho-phosphorus concentrations are 1-2 mg/L to ensure sufficient nutrients. Note that total Kjeldahl nitrogen and total phosphorus are not used, as these may contain organically-bound nutrients, not rapidly biologically available ("bug bodies").

## **Zoogloea Bulking and Foaming**

A special case related to slime bulking is zoogloal bulking. Here, fingered zoogloea proliferate in activated sludge to the extent that sludge settling is hindered. Zoogloea overgrowth also causes reduced sludge dewatering. The responsible organism is *Zoogloea ramigera*, the "classical" floc-former. Here, large masses of this dendritic floc-former may physically interfere in sludge settling and compaction similar to filamentous bulking.

Zoogloea occur at high F/M conditions and when specific organic acids and alcohols are high in amount due to septicity or low oxygen conditions. Note that the sludge polysaccharide values as measured by the anthrone test are normal (10-20%) even when zoogloea are high in amount, due to the particular types of biopolymers formed by these bacteria (amino-sugars that don't react in the anthrone polysaccharide test). The anthrone test is a good way to separate a zoogloea overgrowth problem from a low nutrient polysaccharide problem.

## **Filamentous Bulking**

Filamentous bulking and foaming are common and serious problems in activated sludge operation, affecting most activated sludge plants at one time or another. Filamentous bulking is the number one cause of effluent noncompliance today in the U.S.

An understanding of filamentous bulking and foaming, the causative filaments and their causes and control, has steadily increased over the past 20 years since Eikelboom and van Buijsen published their filament identification system in 1981 (Eikelboom and van Buijsen, 1981). This approach to filament identification has been updated and modified by Jenkins et al. (1993, 2003) and has become used worldwide. Once the causative filaments could be identified, at least to a recognized type, their causes could be determined and control measures appropriate to each filament found.

A bulking sludge is defined as one that settles and compacts slowly. An operational definition often used is a sludge with a sludge volume index (SVI) of >150 ml/g. However, each plant has a specific SVI value where sludge builds up in the final clarifier and is lost to the final effluent, which can vary from a SVI <100 ml/g to >300 ml/g, depending on the size and performance of the final clarifier(s) and hydraulic considerations. Thus, a bulking sludge may or may not lead to a bulking problem, depending on the specific treatment plant's ability to contain the sludge within the clarifier.

A certain amount of filamentous bacteria can be beneficial to the activated sludge process. A lack of filamentous bacteria can lead to small, easily sheared flocs (pin-floc) that settle well but leave behind a turbid effluent. Filaments serve as a "backbone" to floc structure, allowing the formation of larger, stronger flocs. The presence of some filaments also serves to catch and hold small particles during sludge settling, yielding a lower turbidity effluent. It is only when filaments grow in large amounts (approximately  $10^7$  um filaments per gram of activated sludge) that hindrance in sludge settling and compaction occurs. In concept, bulking can be envisioned as

the physical effects of the filaments on the close approach and compaction of the activated sludge flocs. Depending on the type of filament involved, two forms of interference in sludge settling occur: (1) interfloc-bridging - where the filaments extend from the floc surface and physically hold the floc particles apart; and (2) open-floc structure - where the filaments grow mostly within the floc and the floc grows around and attached to the filaments. Here, the floc becomes large, irregularly-shaped, and contains substantial internal voids. The untrained observer often overlooks this latter type of bulking.

A bulking sludge can result in the loss of sludge inventory to the effluent, causing environmental damage and effluent violations. In severe cases, loss of the sludge inventory can lead to a loss of the plant's treatment capacity and failure of the process. Additionally, disinfection of the treated wastewater can become compromised by the excess solids present during bulking. In less severe cases, bulking leads to excessive return sludge recycle rates and problems in waste activated sludge disposal. Many problems in waste sludge thickening are really filamentous bulking problems.

The true incidence of bulking in the U.S. is unknown but has been estimated to affect at least 60% of plants, either continuously or intermittently. Recent work in Colorado suggests that at least 90% of activated sludge plants experience a bulking episode at least once during the year. Bulking may be one of the main reasons why approximately 50% of U.S. activated sludge plants don't consistently meet their effluent discharge standards.

Early microbiological investigations into filamentous organisms found in activated sludge were hampered by a lack of knowledge concerning the types of filaments that may occur. Usually, *Sphaerotilus natans* was diagnosed, often without adequate identification. However, it is now known that approximately 25 different filamentous bacteria commonly occur in activated sludge and each may lead to operational problems. D.H. Eikelboom in Holland (*Water Research* 9:365, 1975) provided a rational basis to "identify" the different filamentous bacteria found in activated sludge. This identification system is based on filament characteristics as viewed under phase contrast microscopy for live samples (*in situ*) and two simple staining reactions: the Gram and Neisser stain. Each filament can be "classified" using a four-digit code, avoiding the earlier problems of lack of specific scientific names. This is important as many of the filaments found in activated sludge have not been isolated in pure culture and hence their identity remains unknown. As these filaments are isolated and properly named (a current research thrust), generic names replace the four digit number code. Hence, the current list of filaments is a hybrid between numbers and genus names. Currently there are 24 recognized filaments (or groups of related filaments in some cases) that cause activated sludge bulking or foaming. These are given in Table 1.

**Table 1. Recognized Filaments That Cause Activated Sludge Bulking or Foaming**

|                                    |                                       |
|------------------------------------|---------------------------------------|
| <i>Sphaerotilus natans</i>         | <i>Microthrix parvicella</i> *        |
| type 1701                          | <i>Nocardia</i> spp.**                |
| <i>Haliscomenobacter hydrossis</i> | <i>Nostocoida limcola</i> I, II & III |
| type 021N                          | type 0961                             |
| <i>Thiothrix</i> I and II          | type 0581                             |
| <i>Beggiatoa</i> spp.              | type 0092                             |
| type 0914                          | type 0411                             |
| type 0041                          | type 1863**                           |
| type 0675                          | fungi                                 |
| type 1851                          | actinomycetes                         |
| type 0803                          |                                       |

-----  
 \* this filament causes both bulking and foaming.

\*\* these filaments cause foaming only.

Causes for almost all of the different filaments are now known (there is always a need to improve this information). Filament causes have been determined using three separate approaches. First, a number of filaments have been isolated in pure culture and their competitive growth abilities examined in laboratory studies. Many of these studies are summarized by Jenkins et al. (1993; 2003). This approach has been successful for *S. natans*, type 1701, *Haliscomenobacter hydrossis*, type 021N, *Thiothrix* I and II, and *Microthrix parvicella*.

Second, the author has microscopically examined and identified the filaments in over 10,000 activated sludge samples over the past 20 years. This extensive database has been analyzed for positive and negative statistical associations between the different filaments. This has resulted in a number of positive associations between filaments of known and unknown causes, establishing a probable cause for the filament of unknown cause. Alternately, a filament of unknown cause may be negatively associated with a filament of known cause, indicating that these filaments do not share a common cause.

Third, practical experience at trial and error successful control methods in plants with a bulking or foaming problem has shown the cause for some filaments not found in the above approaches.

## CAUSES OF FILAMENTS

A summary of the conditions that cause filament growth and the filaments associated with each of these conditions is given in Table 2. There are six environments or growth conditions that cause the overgrowth of filaments in activated sludge. Four of these occur in municipal wastewater systems while all six occur in industrial wastewater systems, with two specific only

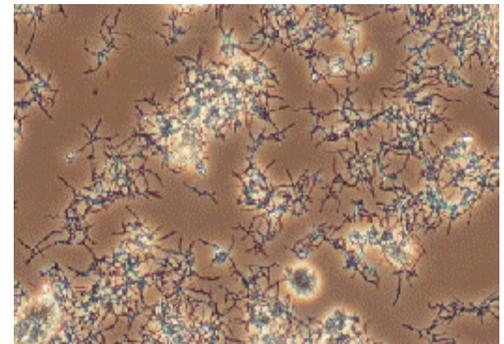
to industrial systems (low nutrients and low pH). Many of the filaments have been associated with other causes in the past, but recent work has indicated the causes given in Table 2 as the primary reason for their growth. Other modifying conditions may apply to some filaments, and these are discussed below.

**Table 2. Causes of Filament Growth in Activated Sludge**

| <u>Cause</u>                          | <u>Filaments</u>   |
|---------------------------------------|--|
| 1. Low Dissolved Oxygen Concentration | <i>Sphaerotilus natans</i><br>type 1701<br><i>Haliscomenobacter hydrossis</i>  |
| 2. Low F/M                            | type 0041<br>type 0675<br>type 1851<br>type 0803   |
| 3. Septicity                          | type 021N<br><i>Thiothrix</i> I and II<br><i>Nostocoida limicola</i> I,II,III<br>type 0914<br>type 0411<br>type 0961<br>type 0581<br>type 0092 |
| 4. Grease and Oil                     | <i>Nocardia</i> spp.<br><i>Microthrix parvicella</i><br>type 1863  |
| 5. Nutrient Deficiency                |  |
| Nitrogen:                             | type 021N<br><i>Thiothrix</i> I and II   |
| Phosphorus:                           | <i>Nostocoida limicola</i> III<br><i>Haliscomenobacter hydrossis</i><br><i>Sphaerotilus natans</i>   |
| 6. Low pH                             | fungi  |



S. natans (1000X)



Nocardia Foam (200X)

-----  
 Note that *H. hydrossis* was previously listed as a low F/M filament. This filament is caused by low DO, but grows relatively slowly and only occurs at lower F/M and a longer sludge age. Lower F/M is not its cause, only where it occurs.

Six specific causes of filament growth and bulking are currently recognized (see Table 2). The information in Table 2 is now used in reverse to the way that it was developed -- from the identification of the most significant filaments present in a bulking sludge, the "cause" for such growth can be determined. Note that some filaments have more than one cause as shown in Table 2. The combination of conditions listed may favor bulking by a particular filament more so than any single condition. It is important to perform filament identification early in a bulking episode to identify the causative filament. Once bulking continues for some time, process upset can lead to the proliferation of other filament types (secondary filaments) which can confuse diagnosis of the real cause.

Today, many activated sludge plants regularly monitor the occurrence and abundance of filaments in their sludge, which has become an important process control tool. This often leads to "heading off" a bulking episode before it becomes serious. Since the microbial population in activated sludge changes slowly in most cases, generally requiring 2-3 sludge ages to radically change, this microscopic observation needs to be performed only at weekly intervals. However, during a period of bulking onset or during application of remedial actions such as chlorination, daily observation of the activated sludge is warranted.

### **Filamentous Foaming**

A brief review of activated sludge foams and their causes is given in Table 3. Use of microscopic examination can readily diagnose most of these, particularly when filaments are involved.

**Table 3. Description and Causes of Activated Sludge Foams**

| <b>Foam Description</b>                                       | <b>Cause(s)</b>  |
|---|--|
| thin, white to grey foam                                      | low cell residence time or "young" sludge (startup foam)                                 |
| white, frothy, billowing foam                                 | once common due to nonbiodegradable detergents (now uncommon)                            |
| pumice-like, grey foam (ashing)                               | excessive fines recycle from other processes (e.g. anaerobic digesters)                  |
| thick sludge blanket on the final clarifier(s)                | denitrification  |
| thick, pasty or slimy, greyish foam (industrial systems only) | nutrient-deficient foam; foam consists of polysaccharide material released from the floc |
| thick, brown, stable foam enriched in filaments               | filament-induced foaming, caused by <i>Nocardia</i> , <i>Microthrix</i> or type 1863     |

Three filamentous organisms can cause activated sludge foaming: *Nocardia* and *Microthrix parvicella* (commonly), and type 1863 (rarely). Nocardial foaming appears to be the most common and occurs at approximately 40% of activated sludge plants in the U.S.

Nocardial foam occurs as a thick, stable, brown foam or "scum" inches to many feet thick on aeration basin and final clarifier surfaces. Normal scum traps (too small) and water sprays (too weak) may be useless to control this type of foam. This foam consists of activated sludge solids (flocs) containing large amounts of *Nocardia* filaments growing from their surface and is quite stable, compared to most other foams, due to the physical "interlocking" of the *Nocardia* filaments. These foams are easy to diagnose microscopically - they are dominated by branched, Gram positive filaments and a simple Gram stain of the foam is all that is needed. The analysis should include comparison to the underlying MLSS (prepare both samples for Gram staining on the same slide). A true Nocardial foam will contain 10-100 fold more *Nocardia* than the underlying MLSS. Nocardial foams also contain substantial lipid concentrations (hexane extractable), up to 40% of dry weight versus 5-10% for *Nocardia*-free activated sludge solids (whether this lipid content of foams is due to the *Nocardia* themselves or to entrapped grease and fat is not clear). In addition, these foams contain significant entrapped air, with a bulk density of approximately 7 g/cc.

Nocardial foams occur in all types of plants, with no particular association with specific modes of operation or aeration. These foams may be more severe in plants with fine bubble or jet aeration and in oxygen activated sludge plants. These foams also occur equally in plants treating domestic, industrial and mixed wastes. Industrial wastes promoting *Nocardia* growth (and foaming) include dairy, meat and slaughterhouse, food processing, pharmaceutical, and any others that contain a significant amount of grease, oil or fat. Nocardial foaming is also associated with high-density restaurant operation in recreational areas (e.g. ski resorts and summer camps). Nocardial foaming has been observed to be caused by treatment of locomotive and truck washing wastes.

Severe Nocardial foams cause a number of operational problems. These include aesthetics, odors, and safety hazards if they overflow basins to cover walkways and handrails. In cold weather these foams can freeze, necessitating "pick and shovel" removal. Foam may escape to the effluent, increasing effluent suspended solids and compromising disinfection. In covered aeration basins, foam can accumulate to exceed the available hydraulic head for gravity flow of wastewater through the basin. Process control can be compromised if a significant fraction of a plant's solids inventory is present in the non-circulating foam (e.g. up to 40% of the total solids inventory can be present in such foams and process control calculations may not be correct).

There should be some concern expressed for the handling of Nocardial foams. The most common *Nocardia* species found in such foams, such as *N. amarae*, are not pathogenic to laboratory animals; however, other less frequently isolated actinomycete strains are known opportunistic human pathogens (e.g. *N. caviae*, *N. brasiliensis*, *N. asteroides* and strains of *Mycobacterium*). No actual infection has been documented, however, treatment plant workers and nearby residents may be at risk.

## **PRACTICAL CONTROL METHODS FOR FILAMENTOUS BULKING AND FOAMING**

The start of any problem solving has to involve microscopic examination of the activated sludge. This reveals whether the problem is, or is not, caused by filaments. If caused by filaments, and most are, identification of the causative filament(s) yields a direction or approach to take for the remedy, as shown in Table 2.

Although a myriad of solutions to bulking have been used (some involving witchcraft), several methods are most practical and proven. These include both short term (treating the symptoms) and long term (treating the cause) changes in operation.

### **Short Term Control Methods**

Short term measures include: "sludge juggling" - changes in return activated sludge (RAS) rates and in waste feeding points; polymer and coagulant addition to aid sludge settling; and chlorination.

#### **Sludge Juggling**

Several methods useful for intermittent bulking problems, but which will not solve a chronic problem, are manipulation of RAS flow rate and manipulation of waste feed points to the aeration basin to minimize the adverse effects of a bulking sludge.

It should be obvious that one must remove solids from the final clarifier faster than they are added. Therefore, the RAS flowrate must be increased in a bulking situation to prevent loss of solids to the effluent. There is a limit to the increase in RAS flowrate as the increased return flow to the system hydraulically pushes more sludge from the clarifier, making effluent TSS losses worse. Some operators report success in bulking control by holding sludge in the clarifier for lengthy time periods. This may work for some filaments (probably by creating septic and toxic conditions), however, in other cases it may worsen the problem (for example, by encouraging sulfide-oxidizing filaments).

A reduction in solids loading to the clarifier can be achieved by a reduction in the system's sludge inventory (a reduction in the aeration basin MLSS concentration). However, this may be detrimental by actually encouraging filament growth (discussed later). A change to step feeding of wastes, where possible, can reduce the MLSS concentration in the clarifier feed without reducing the system's sludge inventory. Here, the MLSS concentration is highest at the head end of the aeration basin (a form of sludge storage) and is decreased in the clarifier feed, thus reducing clarifier loading due to MLSS dilution with wastes. This redistribution of solids in the system usually takes less than one day.

## **Polymer and Coagulant Addition**

There exist several methods of chemical addition to enhance activated sludge settling. Most used are synthetic, high molecular weight, anionic polymers alone or in combination with cationic polymers that serve to overcome the physical effects of filaments on sludge settling. These are usually added to the MLSS as it leaves the aeration basin or to the secondary clarifier center well. Use of polymer does not significantly increase waste sludge production but can be quite expensive, up to \$450. per million gallons treated (obviously this is only used if absolutely necessary). A polymer supply company should be consulted for advice on selection of a polymer and its dosage (the chemical composition of most polymers is a trade secret). Jar testing should be performed to determine the type of polymer needed and its dosage, which is quite plant specific. Further, this jar testing needs to be repeated often, as the needed polymer and its dosage can change, particularly if the filament type(s) change.

In some instances, inorganic coagulants/precipitants such as lime or ferric chloride can be beneficial. These produce a voluminous precipitate that sweeps down the activated sludge, improving settling. Sludge production may be significantly increased if these are used. The weighting action of inert biological solids has also been used to aid sludge settling in activated sludge modifications such as the Hatfield or Kraus processes that recirculate anaerobic digester contents through the aeration basin. Some papermills intentionally release fiber or clay to the wastewater system to help sludge settling during a bulking episode.

## **Chlorination**

Two toxicants, chlorine and hydrogen peroxide, have been used successfully to control filamentous organisms and stop a bulking episode. Chlorine is most widely used as it is inexpensive and available on-site at most plants, and only this will be discussed here. Chlorination for bulking control is widespread, used by more than 50% of plants.

The goal of chlorination is to expose the activated sludge to sufficient chlorine to damage filaments extending from the floc surface while leaving organisms within the floc largely untouched. Filamentous and floc-forming bacteria do not appear to significantly differ in their chlorine susceptibility. Chlorine dosage is adjusted such that its concentration is lethal at the floc surface but is sublethal within the floc, due to chlorine consumption as it penetrates into the floc. This is analogous to "peeling an orange" and removing the filaments attached to its surface. It should be pointed out that chlorination is not a cure-all for all activated sludge microbiological problems. Chlorination will actually make problems worse if the problem is non-filamentous, e.g. slime bulking or poor floc development.

Chlorine can be applied from a chlorinator using chlorine gas feed or as a liquid hypochlorite. A separate chlorinator should be dedicated to bulking control and an independent rotameter and sampling point in this chlorine line is needed. The chlorine addition point is of most importance and should be at a point where the sludge is concentrated, raw wastes are at a minimum, and at

a point of good mixing. Poor initial mixing results in the consumption of large amounts of chlorine without bulking control. Three common chlorine addition points are: (1) into the RAS stream at a point of turbulence (elbows in pipes; into the volute or discharge of RAS pumps; and into and below the liquid level in a riser tube of an airlift RAS pump); (2) directly into the final clarifier center well or feed channel; and (3) in an installed sidestream where the MLSS is pumped from and returned to the aeration basin.

Chlorine addition to the RAS line(s) is the method of choice and most generally successful. Chlorine addition to the aeration basin usually does not work and often causes floc dispersion and system damage.

The two most important parameters are chlorine dosage and frequency of exposure of the activated sludge to chlorine. Chlorine dose is measured conveniently on the basis of sludge inventory in the plant – termed the overall chlorine mass dose. Effective chlorine dosages usually are in the range 1-10 pounds chlorine/1000 pounds MLVSS inventory/day (2-4 should work). Chlorine dosage should be started low and increased until effective. Sludge settleability usually improves within 1-3 days if the correct chlorine dosage is applied.

Most domestic waste plants can achieve a frequency of exposure of the activated sludge inventory to chlorine of three or greater per day (the optimum) in the RAS line. The needed frequency is a function of the relative growth rates and efficiencies of kill of filamentous and floc-forming organisms. Success has been achieved at frequencies as low as one per day but not less, however, this is plant specific.

In plants with long aeration basin hydraulic residence times (industrial waste plants), the daily solids flux in the RAS line is generally too low for successful bulking control using chlorine at this point alone. Here, most success has been achieved using multiple chlorine addition points such as the RAS line(s) and the final clarifier(s) in combination.

A target SVI value (or other sludge settling measure) must be set and chlorine applied only when this value is exceeded. This is determined by trial-and-error at each plant. It should be remembered that chlorination controls filament extension from the floc surface and merely reduces the symptoms of bulking. Filaments will regroup rapidly, often with a vengeance, after termination of chlorination since the cause of the bulking has not been addressed.

Signs of over chlorination are a turbid (milky) effluent, a significant increase in effluent TSS, a loss of the higher life forms (protozoa), and a reduction in BOD removal. It is normal to see a small increase in effluent suspended solids and BOD<sub>5</sub> when using chlorine for bulking control.

Microscopic examination of the activated sludge during chlorination is recommended to control chlorine application. Chlorine effects on filaments include, in order: a loss of intracellular sulfur granules (in those filaments that have these); cell deformity and cytoplasm shrinkage; and finally filament breakup. For sheathed filaments, the sheath is not destroyed by chlorine. Here, sludge settle ability remains poor until the sheaths are washed out of the system by sludge wasting, which can take 1-2 sludge ages. Chlorine use should be stopped when only empty sheaths remain and not continued until the SVI falls, which can result in over chlorination. As a general

observation, chlorination should be stopped when about 70% of the cells are damaged or missing in a filament.

One argument to chlorine use in bulking control is the possibility of the production of chlorination by-products. This is unlikely since the chlorine is short-lived in activated sludge (minutes) and applied at a low dosage (lower than used in effluent disinfection). Chlorine cannot be used if waste constituents react with chlorine to form by-products such as petrol-chemical or phenol wastes.

### **Long Term Control Methods**

Long term measures include activities such as: control of influent waste septicity (organic acids and H<sub>2</sub>S); nutrient additions (industrial waste systems only); changes in aeration; and changes in biomass concentration or changes in waste feeding pattern.

These control measures will be expanded upon below. In addition, control of foaming problems will be addressed at the end of this paper.

### **Low Dissolved Oxygen Problems**

In general, the rate of BOD removal is near maximum at 1.0 mg/L dissolved oxygen (DO) concentration, while the rate of nitrification is near maximum at 2.0 mg/L DO. However, the actual DO concentration within the biological flocs is less than that measured in the bulk solution around the flocs, due to oxygen use as it penetrates into the flocs.

Low aeration basin DO leads to bulking by several filaments: *S. natans*, type 1701 and *H. hydroxsis*. The DO concentration needed to control these filaments is not a constant, rather, is a function of the organic loading rate (F/M) of the system (Palm et al., 1980). At F/M values of about 0.5 or less, a DO concentration of 2.0 mg/L usually controls these filaments. However, at higher F/M values a DO value of greater than 2.0 mg/L may be needed. This is due to the need to keep the floc interiors aerobic, and this is more difficult at higher F/M values where the OUR of the sludge is high. The DO concentration in the bulk solution around the flocs has to be high enough to maintain an aerobic floc interior. Since oxygen moves into the floc by diffusion, its bulk concentration needs to be high enough to reach the floc centers before becoming depleted. A bulk solution DO concentration of 4.0 mg/L or more has been needed to prevent these filaments in some industrial wastewater systems operated at high F/M values of >0.5. Note that raising the MLSS concentration causes a reduction in the system F/M and OUR, and this change can alleviate oxygen limitation within the flocs and control the low DO filaments. Low DO filaments have been eliminated from many systems by an increase in the MLSS concentration.

Control of low DO bulking is by raising the aeration basin DO concentration, if possible, or by raising the aeration basin MLSS concentration to decrease the F/M (both should be done concurrently). Note that this action is opposite to what intuition directs -- to reduce the MLSS concentration, since less biomass needs less oxygen (wrong! - the F/M is actually increased at lower MLSS concentration). An increase in the RAS rate may also be beneficial, as this brings biomass back to the aeration basin where it helps lower the F/M.

A common experience is that it takes a higher aeration basin DO concentration to "cure" low DO bulking than to prevent it in the first place. Often, a short term bulking control option is used, most often chlorination, to control this bulking problem.

### **Wastewater Septicity and Organic Acids**

Septicity is the term used to describe the condition where the wastewater becomes anaerobic and anaerobic bacteria ferment organic materials to organic acids such as acetic, propionic, butyric and valeric acids. Sulfate reducing bacteria also convert sulfate to hydrogen sulfide at this condition. A septic wastewater thus contains a relatively high amount of organic acids and hydrogen sulfide.

A number of filaments grow on organic acids and some hydrogen sulfide (type 021N, *Thiothrix* I and II, type 0914 and *Beggiatoa*). Observation of these filaments with intracellular sulfur granules is a tip-off of a septicity problem and high hydrogen sulfide concentration. An organic acid concentration of >100 mg/L and a sulfide concentration of >1-2 mg/L usually causes an overgrowth of these bacteria.

Septicity can occur ahead of the plant, in the collection system, or can occur in the treatment plant. Common locations of septicity in a collection system include lift stations, force mains and long, stagnant lines. Influent septicity is usually indicated by odors (sulfide or "rotten egg" smell), a dark color to the wastewater, and corrosion.

High amounts of organic acids and sulfides also occur in septage. These filaments may occur due to a high loading of septage. Some industrial wastewaters also contain a high amount of organic acids, such as wastewater from pickling and textile dyeing operations.

Septicity can also occur in the treatment plant. Common locations of septicity include poorly aerated or poorly mixed equalization basins; septic primary clarifiers; poorly mixed aeration basins; septic final clarifiers; and septic sludge processing side-stream returns. A common cause of septicity is the use of a primary clarifier as a sludge thickening tank or return of waste activated sludge to a primary clarifier.

Septicity can be tested for by analyzing the various basin influents and effluents for their organic acid content, using the distillation and pH titration method in *Standard Methods* (the same test as used for anaerobic digester operation). An organic acid concentration >100 mg/L is high and would account for the growth of these filaments. Hydrogen sulfide can also be tested for

using one of the readily available HACH Chemical Co. test kits. A hydrogen sulfide concentration  $>1-2$  mg/L causes the growth of type 021N and *Thiothrix* I and II.

Note that some of the filaments now listed as septicity filaments (i.e. type 0961, type 0581 and type 0092) were previously listed as low F/M filaments. It has been learned that these filaments are actually caused by septicity and organic acids, but these grow slowly and only occur at a lower F/M. Low F/M is not their cause, only where they occur.

There is some selection of these filaments according to the type of organic acids present. Type 021N and *Thiothrix* I and II prefer simple organic acids such as acetic, propionic and butyric acids. Type 0581 and type 0092 appear to prefer higher carbon number and more complex organic acids. For example, type 0092 is a particular problem when the wastewater contains citric acid from industry.

Influent wastewater septicity can be treated by pre-aeration (which releases odors), chemical oxidation (chlorine, hydrogen peroxide, or potassium permanganate), or chemical precipitation (ferric chloride). Septicity in the collection system can be prevented by addition of sodium nitrate as an "oxygen source" (commercially available as Bioxide).

If the influent wastewater septicity cannot be reduced, then the aeration basin can be configured to allow better treatment of organic acids and sulfides. The organic acid concentration and sulfide concentration in contact with the biomass can be reduced by using completely-mixed or step-fed aeration basin conditions. A plug flow aeration basin configuration or a sequencing batch reactor is the worse case for this condition.

### **Low F/M Problems and Selectors**

Four filaments -- type 0041, type 0675, type 1851 and type 0803 -- are specifically caused by low F/M conditions, usually below an F/M of 0.15, and corresponding longer sludge age. Their specific mechanism of successful competition is not known. These may simply be slow growing and occur only at longer sludge age associated with lower F/M. These may also grow on particulate BOD, which would be used after the more readily degradable soluble BOD is exhausted. It has also been suggested that these filaments compete successfully due to a low endogenous maintenance energy requirement.

Control of low F/M bulking can be achieved by reducing the aeration basin MLSS concentration and increasing the F/M (manipulating the "M" component). Lowering the MLSS concentration may not be suitable for many plants as this may cause the loss of nitrification and increase waste sludge production. Any change in operation that effectively increases the substrate concentration available to the activated sludge and introduces batch or plug-flow characteristics to the aeration basin, even on a short-term basis, will help combat low F/M bulking. These include: compartmentalization of aeration basins; fed-batch operation; intermittent feeding of wastes; and use of a selector. These latter methods do not reduce the MLSS concentration in the system. Incidentally, step feeding of wastes, recommended for low DO bulking, can lead to low F/M bulking, so this may need to be changed.

Filamentous bulking by the low F/M filaments is most common in completely-mixed aeration basin systems at low aeration basin substrate (BOD) concentration. Intermittently-fed and plug-flow systems are more resistant to this type of bulking. This observation has led to the use of selectors where the RAS and the influent wastewater mix for a short time prior to the main aeration basin.

A selector is a mixing basin or channel where RAS and influent wastes mix prior to the aeration basin. Selector design is empirical at this time. Successful examples involve a 15-30 minute contact time of the RAS and influent waste; are aerated; and achieve at least an 80% removal of soluble BOD<sub>5</sub> through the selector. Several newer designs are either operated anoxic (no free oxygen but nitrate present) or anaerobic, however, these are too new to state their general usefulness. Design and operation of selectors for filament control is beyond the scope of this paper, and the interested reader is directed to Jenkins et al. (1993, 2003) for further information.

A selector can be too large or too small in size to properly function. The goal is to provide a short term, high substrate condition which favors certain floc-formers but which discourages filaments. These floc-formers appear to rapidly store BOD as cellular storage products in the selector, which they use later for growth in the main aeration basin (they pack their own "lunch bags" in the selector). If the selector is too large, the substrate concentration achieved may not be high enough to encourage these special floc-formers and discourage filaments. If too small, insufficient time may be available for substrate uptake and storage. Also, a selector that is too small may cause the floc-formers to shunt carbonaceous substrate to exocellular polymer that can increase the SVI of the sludge ("slime bulking") and pose problems in waste sludge dewatering. The best approach is to try several selector sizes, using a larger basin or channel with movable baffles or exit gates.

Selectors are specific tools to combat low F/M filaments and are not needed by all plants. There have been many instances of inappropriate selector use where they actually made the problem worse, for example, where bulking was caused by low DO, nutrient deficiency or septicity.

### **Nutrient Deficiency**

Nitrogen and phosphorus can be growth limiting if not present in sufficient amounts in influent wastewater, a problem with industrial wastes and not domestic wastes. In general, a BOD<sub>5</sub>:N:P weight ratio in the wastewater of 100:5:1 is needed for complete BOD removal. Other nutrients such as iron or sulfur have been reported as limiting to activated sludge, but this is not common.

Signs of nutrient deficiency include: filamentous bulking by several specific filaments (see Table 2); a viscous activated sludge which exhibits significant polysaccharide ("slime") when "stained" with India ink; and foam on the aeration basin which contains a high amount of polysaccharide (which has surface active properties). One check for nutrient deficiency is to be sure that at

least 1.0 mg/L total inorganic nitrogen (TIN = ammonia plus nitrite plus nitrate) and 0.5 - 1.0 mg/L ortho-phosphorus (soluble phosphorus) remain in the effluent at all times. The best location to test for nutrient residuals is the feed from the aeration basin to the final clarifier(s). Sometimes nutrients are released from the sludge at endogenous conditions in the final clarifier(s), falsely elevating the effluent nutrient concentrations.

If needed, nutrients should be dosed to the incoming wastewater or the aeration basin. Nitrogen sources include: anhydrous ammonia, urea, and ammonium salts ((NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, NH<sub>4</sub>Cl or NH<sub>4</sub>NO<sub>3</sub>). Both ammonia and nitrate are nitrogen sources for growth. Phosphorus sources include: H<sub>3</sub>PO<sub>4</sub>, Na<sub>2</sub>PO<sub>4</sub> and (NH<sub>4</sub>)<sub>2</sub>PO<sub>4</sub> (among others).

In systems treating mixed domestic and industrial wastes, only total inorganic nitrogen (TIN) and soluble ortho-phosphorus should be used to calculate nutrient availability. Organically combined nitrogen and phosphorus (Kjeldahl nitrogen and total phosphorus) may not be hydrolyzed fast enough by the microorganisms in the activated sludge to keep pace with BOD use. Also, the nutrient addition rate should match the influent BOD strength as much as possible, as short term BOD spikes can cause an aeration basin to become nutrient limited for short time periods (which can cause bulking) even though the 24-hour average BOD:N:P ratio is satisfactory.

## **Foaming Control**

Three filaments cause foaming: *Nocardia*, *M. parvicella* and type 1863. All of these filaments grow on grease and oil, and these can become a problem when grease and oil are high in amount in the influent wastewater. Systems that lack primary clarification (the main grease and oil removal mechanism) appear to suffer more foaming problems. Communities with enforced grease and fat ordinances appear to suffer less from foaming problems. Also, disposal of septage, which contains substantial grease and oil content, to small activated sludge systems has been associated with foaming problems.

Note that *Nocardia* here is used as a group name rather than a specific species. Recent work has shown that a number of actinomycetes can cause foaming and include *Nocardia amarae*, *N. pinensis*, *N. rhodochrus* and other *Nocardia*-like species. These are often collectively referred to as the Nocardioforms, or the foam-causing actinomycetes.

*Nocardia* and *M. parvicella* also occur at a longer sludge age. The sludge age at which these filaments can be controlled is a function of the wastewater temperature, being lower at higher temperature. *Nocardia* appears to be favored at higher aeration basin temperatures and *M. parvicella* at lower aeration basin temperatures. *Nocardia* can usually be controlled by a sludge age below 6-8 days and *M. parvicella* at a sludge age below 8-10 days at moderate wastewater temperatures. However, many plants have had to reduce the sludge age to less than 2 days for *Nocardia* control, and this may be inconsistent with other process goals, such as nitrification or sludge handling capability.

A third factor in the growth of *Nocardia* and *M. parvicella* is septicity or low oxygen conditions. Note that the combination of grease and oil, longer sludge age, and septicity or low oxygen conditions is needed for these filaments to overgrow the system and cause foaming. In this regard, *Nocardia* and *M. parvicella* can be considered “low DO filaments”, although low DO per sec doesn’t cause them without the other two factors.

*Nocardia* and *M. parvicella* appear to grow better on unsaturated fatty acids in comparison to saturated fatty acids. A change in the US diet from saturated to unsaturated fatty acids is one reason why foaming by these bacteria is more prevalent today than it was 20-30 years ago. Also, anaerobic bacteria break down fatty acids by first modifying them to an unsaturated form. This may be why septicity is one of the causes for these bacteria, providing them with a source of unsaturated fatty acids.

Type 1863 differs in growing at a low sludge age, usually less than 3-4 days. It indicates a high amount of grease and oil and a young sludge condition. Many type 1863 foaming episodes have been caused by a reduction in primary clarification when units were removed from service for repair or cleaning and grease and oil concentration increased in the aeration system.

Control of *Nocardia* and *M. parvicella* foaming is difficult. Chemical antifoam agents have not proven generally effective, probably because these act on chemical surfactants and not on a solids-stabilized foam. Many plants reduce aeration to control foaming, but process performance may suffer if oxygen becomes limiting. Further, low oxygen-induced bulking may occur when this is done.

Physical control of foams is most widely practiced using enlarged surface scum traps and forceful water sprays (often containing 50 mg/L chlorine). Many foams reach problem levels because they build up on these surfaces and are not removed. Foam should be removed entirely from the system and not recycled back into the plant, for example, into the headworks. Foam disposal into aerobic or anaerobic digesters can result in foaming there, so this should be avoided.

Return sludge chlorination has not eliminated *Nocardia*, although it often helps, due to *Nocardia's* growth mostly within the activated sludge flocs where it isn't readily contacted by chlorine. Also, much of the *Nocardia* may be present on the aeration basin surface and this doesn't go through the RAS line to see chlorine. RAS chlorination is more useful for foams caused by *M. parvicella*.

Many anaerobic digester foaming incidents may be attributed to treatment of *Nocardia*-containing waste activated sludge. A nationwide survey in 1981 by the American Society of Civil Engineers revealed that as many as half of the anaerobic digesters in use had experienced foaming at one time or another. It was recently reported that 54% of 26 California activated sludge plants surveyed had recently experienced anaerobic digester foaming (Van Niekerk et al., JWPCF 59:249, 1987). Here, it is important to remember that *Nocardia* cells float, dead or alive, due to their hydrophobic cell surface. Even though *Nocardia* are strict aerobes, their cells are readily floated and cause foaming even under anaerobic conditions.

*Nocardia* and *M. parvicella* are controlled by addressing all three causative factors above. A reduction in the grease and oil content of the wastewater is needed, either through source control or improved operation of the primary clarifier (if present) to better remove grease and oil. These filaments are usually controlled by a reduction in the system sludge age as given above. Septicity, if present, needs to be controlled, and the aeration basin DO concentration should be raised. Note that higher aeration causes more foam formation, due to the physical action of more air present. Many operators reduce aeration when foaming occurs to reduce the foam, but this only causes more filament growth in the long term.

## **SUMMARY**

Most activated sludge upsets and loss of process control are caused by one of several microbiological problems which include poor floc formation, pin floc, dispersed growth, filamentous and slime bulking, filamentous foaming, zoogloal bulking, nitrification and denitrification problems and toxicity. Use of the microscopic examination and the OUR test are invaluable tools in troubleshooting the activated sludge process. Once the cause of the problem or upset is known, specific remedies appropriate for the problem can be used. Short term control methods such as chlorination are often used to quickly stop a bulking problem. However, the best approach is to investigate the long-term control methods suitable for the problem that is occurring to achieve trouble free operation.

## **REFERENCES AND ADDITIONAL INFORMATION**

Eikelboom, D.H and van Buijsen, H.J.J., *Microscopic Sludge Investigation Manual*, TNO Res. Inst. for Env. Hygiene, Delft, The Netherlands, 1981.

Jenkins, D., M. G. Richard and G.T. Daigger, *Manual on the Causes and Control of Activated Sludge Bulking and Foaming*, 2<sup>nd</sup> Ed., Lewis Publishers, Boca Raton, FL, 1993; 3<sup>rd</sup> Ed., 2003.

*Activated Sludge Microbiology*, M.G. Richard, Water Environment Federation, Alexandria, VA, 1989.

Palm, J.C., D. Jenkins and D.S. Parker, *Relationship Between Organic Loading, Dissolved Oxygen Concentration and Sludge Settability in the Completely-Mixed Activated Sludge Process*, J. Water Poll. Control Fed. 52:2484, 1980.

Walker, I. and M. Davis, *The Relationship Between Viability and Respiration Rate in the Activated Sludge Process*, Water Research: 575, 1977.

APPENDIX E

NUTRIENT DEFICIENCY CALCULATIONS  
(Source: WEF Manual of Practice OM-9)

A nutrient deficiency will sometimes cause a filamentous bulking problem. The following example shows how to find out if there is a nutrient deficiency, and how to calculate the amount of nutrients to add to correct the problem. Once the chemical feed rate (in lb/day) is determined, the chemical must be fed into the secondary influent, preferably in proportion to the flow. The chemical feed equipment must be set to feed the calculated amount of nutrient during the 24-hour period.

Example A. Calculate the amount of nutrients to add to correct a nutrient deficiency.

Given: Secondary influent BOD<sub>5</sub> = 170mg/L

Secondary influent TKN = 4.5 mg/L

Secondary influent P = 1.0 mg/L

Secondary influent Fe = 0.5 mg/L

Suggested ratio by weight, BOD<sub>5</sub>/N = 100/5 = 20

Suggested ratio by weight, BOD<sub>5</sub>/P = 100/1 = 100

Suggested ratio by weight, BOD<sub>5</sub>/Fe = 100/0.5 = 200

Average daily plant flow, Q = 7.5 mgd

Ammonia/nitrogen atomic weight ratio, NH<sub>3</sub>/N = 17/14 = 1.2

Trisodium phosphate/phosphorus atomic weight ratio, Na<sub>3</sub>PO<sub>4</sub>/P = 164/31 = 5.3

Ferric chloride/iron atomic weight ratio, FeCl<sub>3</sub>/Fe = 162.5/56 = 2.9

Solution

Step 1. Calculate the amount of nutrients needed to achieve the suggested ratios.

$$\text{Nutrient needed, mg/L} = \frac{\text{Secondary influent BOD}_5, \text{ mg/L}}{\text{Suggested weight ratio, BOD}_5/\text{nutrient}}$$

$$\text{N needed, mg/L} = \frac{\text{BOD}_5 \text{ mg/L}}{\text{Suggested ratio, BOD/N}}$$

$$= 170/20$$

$$= 8.5 \text{ mg/L}$$

$$\text{P needed, mg/L} = \frac{\text{BOD}_5 \text{ mg/L}}{\text{Suggested ratio, BOD/P}}$$

$$= 170/100$$

$$= 1.7 \text{ mg/L}$$

$$\text{Fe needed, mg/L} = \frac{\text{BOD}_5 \text{ mg/L}}{\text{Suggested ratio, BOD/Fe}}$$

$$= 170/200$$

$$= 0.85 \text{ mg/L}$$

Step 2. Calculate the difference between the nutrients available and the nutrients needed. If this answer is zero or a negative number, there is no shortage and no nutrients need be added.

$$\text{Nutrient shortage, mg/L} = (\text{Nutrient needed, mg/L}) - (\text{Nutrient available, mg/L})$$

$$\begin{aligned} \text{N shortage, mg/L} &= (\text{N, needed mg/L}) - (\text{TKN available, mg/L}) \\ &= 8.5 - 4.5 \\ &= 4.0 \text{ mg/L} \end{aligned}$$

$$\begin{aligned} \text{P shortage, mg/L} &= (\text{P needed, mg/L}) - (\text{P available, mg/L}) \\ &= 1.7 - 1.0 \\ &= 0.7 \text{ mg/L} \end{aligned}$$

$$\begin{aligned} \text{Fe shortage, mg/L} &= (\text{Fe needed, mg/L}) - (\text{Fe available, mg/L}) \\ &= 0.85 - 0.5 \\ &= 0.35 \text{ mg/L} \end{aligned}$$

Step 3. Calculate the weight of nutrients that need to be added.

$$\text{Nutrient to add lb/day} = (\text{Shortage, mg/L})(Q, \text{mgd})(8.34 \text{ lb/gal})$$

$$\begin{aligned} \text{N to add, lb/day} &= (\text{N shortage, mg/L})(Q, \text{mgd})(8.34 \text{ lb/gal}) \\ &= (4)(7.5)(8.34) \\ &= 250 \text{ lb/day} \end{aligned}$$

$$\begin{aligned} \text{P to add, lb/day} &= (\text{P shortage, mg/L})(Q, \text{mgd})(8.34 \text{ lb/gal}) \\ &= (0.7)(7.5)(8.34) \\ &= 43.8 \text{ lb/day} \end{aligned}$$

$$\begin{aligned} \text{Fe to add, lb/day} &= (\text{Fe shortage, mg/L})(Q, \text{mgd})(8.34 \text{ lb/gal}) \\ &= (0.35)(7.5)(8.34) \\ &= 21.9 \text{ lb/day} \end{aligned}$$

Step 4. Calculate the weight of the commercial chemical to be added per day to supply the needed nutrients.

Chemical, lb/day = (Nutrient to add, lb/day)(Atomic wt ratio) (100%)

For anhydrous ammonia commercial grade solution 80% concentration

$$\begin{aligned}\text{Anhydrous ammonia, lb/day} &= (\text{N to add, lb/day})(1.2 \text{ NH}_3/\text{N})(80\% \text{ concentration}) \\ &= (250)(1.2)(100/100) \\ &= 375 \text{ lb/day}\end{aligned}$$

For trisodium phosphate, commercial grade solution 75% concentration

$$\begin{aligned}\text{Trisodium phosphate, lb/day} &= \frac{(\text{P to add, lb/day})(5.3 \text{ Na}_3\text{PO}_4/\text{P})(100\%)}{\text{Na}_3\text{PO}_4 \text{ concentration } \%} \\ &= \frac{(43.8)(5.3)(100)}{75} \\ &= 310 \text{ lb/day}\end{aligned}$$

For ferric chloride commercial grade solution 39% concentration

$$\begin{aligned}\text{Ferric chloride, lb/day} &= \frac{(\text{Fe to add lb/day})(2.9 \text{ FeCl}_3/\text{Fe})(100\%)}{\text{FeCl}_3 \text{ concentration } \%} \\ &= \frac{(21.9)(2.9)(100)}{39} \\ &= 163 \text{ lb/day}\end{aligned}$$

## APPENDIX F

### Return Chlorination (Bulking) Calculations

### Chlorination for Filament Control at WWTFs

Begin control strategy when Sludge Volume Index (SVI) exceeds \_\_\_\_\_ for three days

Calculate Chlorine Needed:

1. Lbs MLSS Calculation:

$$\frac{\text{_____ mgal}}{\text{Volume \{AT + Clar\}}} \times \frac{\text{_____ mg/L}}{\text{MLSS Conc.}} \times 8.34 = \frac{\text{_____}}{\text{(1)}} \text{ lbs MLSS (Total Solids Inventory)}$$

2. Convert to 1000 lbs MLSS

$$\frac{\text{_____}}{\text{(#1)}} \text{ divided by 1000} = \frac{\text{_____}}{\text{(2)}} \text{ 1000\# MLSS}$$

3. Convert to Pounds of Ch Needed:

$$\frac{\text{_____}}{\text{(#2)}} \times (5-6) = \frac{\text{_____}}{\text{(3)}} \text{ lbs. Cl}_2\text{/day (Calculated Cl}_2\text{ dose)}$$

4. Calculate pounds of return sludge pumped per day:

$$\frac{\text{_____ mgal}}{\text{Return Sludge Flow}} \times \frac{\text{_____}}{\text{RSSS Conc}} \times 8.34 = \frac{\text{_____}}{\text{(4)}} \text{ lbs RSSS}$$

5. Calculate frequency of exposure:

$$\frac{\text{_____}}{\text{(#4)}} \text{ divided by } \frac{\text{_____}}{\text{(#1)}} = \frac{\text{_____}}{\text{(5)}} \text{ Times/day}$$

6. Convert pound of chlorine to gallons of 12% Hypochlorite:

1 gallon of hypochlorite equals 11b of chorine,  
the gallons/.day number is the same a (#3)

$$\frac{\text{_____}}{\text{(6)}} \text{ gal Cl}_2\text{/day}$$

7. Convert gallons to ml/minute

$$\frac{\text{_____}}{\text{(#6)}} \times 2.63 = \frac{\text{_____}}{\text{(7)}} \text{ ml/minute}$$

If the frequency of exposure (#5) is 3 or more, set your pump to deliver the required ml/minute of chlorine (#7). Solution should be added in the return sludge line.

If the frequency of exposure (#5) is less than 3, you need more application points. Set up two or more pumps. Both pumps would then deliver Y2 of (#7). For the second spot, use a turbulent location (effluent end of the aeration tank or clarifier feed channel). For oxidation ditches, install a diffuser line (several openings) just before the rotor that is furthest from the influent feed line and add all the solution there.

You should plan on running the chlorine for 3-6 days. If you usually nitrify, monitor the effluent ammonia daily. If the ammonia goes above 4 mg/L, reduce the chlorine dose. Monitor scope and settleometer for changes. If effective, the SVI should drop into your target range.

## Appendix G

### Settleability Test Procedures

## Settleability Test Procedures

The settleability test is an approximation of how sludge settles in the clarifier. You should always use a 2 Liter Mallory Settleometer or equal. Do NOT use a graduated cylinder for the settleability test (even if *Standard Methods* says to). A 1-gallon wide-mouth mayonnaise jar with a graduation decal is OK in a pinch

### Equipment

- A 2-liter Mallory Settleometer with a wide, plastic stirrer
- A laboratory clock
- A pipette with a suction bulb

### Procedure

1. Collect the sample near aeration tank effluent weirs.
2. Collect a sample from each aeration tank.
3. Run settling tests immediately after collecting the sample
4. Pour fresh well-mixed sample to the line at the top of the settleometer
5. Gently mix with wide paddle and stop current
6. Start timer for 5 minutes
  - Don't Leave! Observe the Settling**
    - The first 5 minutes are critical
    - Observe the floc characteristics, channeling
    - Observe the supernatant quality
    - Record your observations in log or settling test bench sheet
    - Continue with readings every 5 minutes for the first 30 minutes, then every 10 minutes until 60.
  - Read again in 2 hours
    - further compaction?
    - floating sludge?
  - Leave on bench and check after 4 hours
    - Do you observe floating sludge?
      - Rise in 0.5-1.0 hour indicates significant nitrification/denitrification
      - No rise in four hours means little nitrification/denitrification
7. Record results in log or on bench sheet
  - Graph readings, settled sludge volume, ssv in ml, versus time, in minutes
  - Locate “knee of curve” to determine the theoretical optimum settling time

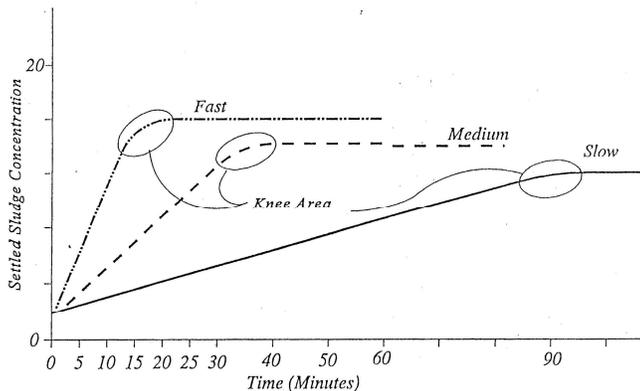


Figure 3-8: Settled Sludge Concentration Curves

## Sludge Volume Index (SVI)

The Sludge Volume Index indicates the relative settleability of the sludge. The SVI is defined as the Volume, in milliliters, occupied by gram of sludge

The SVI is a relative number, but it is useful as index for a given facility. Many factors affect the “accuracy” of the SVI test. You should not compare plants with it because a “good” range for one facility may be very poor for another facility: “Good” SVI readings can be 80 - 300+, depending on plant (clarifiers). We do not recommend calculating RAS Flow using SVI

$$SVI = \frac{SSV_{30} \times 1000 \text{ mg/g}}{MLSS_{\text{mg/L}}}$$

Some prefer svi60 , use ssv60 in calculation

## Diluted Settleability

Diluted settleability can be used to differentiate between filamentous or slime bulking and a “glutted” (too many solids) condition

Make a dilution of 50% MLSS, 50% unchlorinated clarifier effluent and fill a 2-liter Settleometer with some of the diluted sample. Fill another 2-liter Settleometer with 100% mixed liquor.

If the diluted sample settles significantly better than full sample there are too many solids in system. If the settleability of the diluted sample is about the same as the settleability of the undiluted sample, filamentous or slime bulking is probably occurring.



## APPENDIX H

OUR TEST PROCEDURES  
(Source Ronald Schuyler, P.E.)

## OUR Test Procedure

### Equipment:

1. DO Meter with BOD Bottle probe
2. 2 – 300mL BOD Bottles
3. Magnetic stirrer (if BOD Probe does not have a stirrer)
4. Sample
5. Timer
6. Beaker with diameter slightly larger than the BOD Bottle

### Procedure

1. Measure and record DO and temperature at the sample site.
2. Collect 3-4 liters of fresh sample. Aeration tank effluent and/or influent end after RAS has mixed with the aeration influent flow.
3. Pour some mixed liquor in the beaker so that when the BOD bottle is placed in the beaker, the mixed liquor will come up to the neck of the bottle.
4. Thoroughly mix the sample remove an aliquot and aerate it to get the DO above 5 mg/L. this may be done by filling a 1 liter bottle half full of mixed liquor and shaking the bottle gently to aerate the sample
5. Fill a 300 ml sample bottle. Fill to overflowing. Some bubbles will gather at the top. Tilt the BOD bottle to work the bubbles out of the sample.
6. Place the BOD bottle in the beaker. Be sure the mixed liquor level in the beaker remains just below the neck of the BOD bottle.
7. Place the DO probe in the bottle, making sure not to trap any bubbles. Begin stirring the sample. Allow a short time (30 – 60 seconds) for the temperature and the probe to stabilize.
8. Record the DO every minute for 10 minutes, or until the DO drop becomes consistent or until the DO drops below 1 mg/L. Make sure that there is at least 1 mg/L difference between the start and finish of the test.

Note: If the OUR is extremely high values may have to be read every 30 seconds and the initial DO may have to be increased to 7-8 mg/L. If that does not provide a satisfactory test dilute the sample with BOD dilution water, reaerate the sample and complete the test again. Calculate the appropriate dilution factor to obtain the OUR of the original sample.

## OUR calculation

1. Graph the results by plotting DO (in mg/L) on the vertical axis and time (in minutes) on the horizontal axis.
2. Graph the line of best fit of the data. The line should be nearly straight. If there are data at the beginning and/or end of the test that are significantly different from the straight line, disregard that data. The straight line represents the actual microorganism activity.
3. Determine the slope of the line. Pick the points at the beginning and end of the straight line portion. Divide the change in DO between those two points by the change in minutes between those two points.
4.  $OUR = \Delta DO / \Delta Time = \text{mg/L/min}$  if the time is in minutes
5. Multiply by 60 min/hr to get the results in  $\text{mg O}_2/\text{L/hr}$

## SOUR calculations and Interpretation

### Required Information

OUR of the sample

MLSS or MLVSS of the same sample

### Calculation

$$SOUR = \frac{OUR \text{ mg/L/hr} \times 1000 \text{ mg/g}}{MLVSS, \text{ mg/L}}$$

### Interpretation

| Modification                  | SOUR Range                              |
|-------------------------------|---|
| Conventional Activated Sludge | 8-20 $\text{mg O}_2/\text{hr/g VSS}$    |
| Step Aeration                 | 8-20 $\text{mg O}_2/\text{hr/g VSS}$    |
| Extended Aeration             | 3-12 $\text{O}_2/\text{hr/g VSS}$       |
| Contact Stabilization         | 15-30/5-15 $\text{O}_2/\text{hr/g VSS}$ |
| Aerobic Digestion             | <2 $\text{O}_2/\text{hr/g VSS}$         |

Values outside these ranges are not necessarily a problem since your plant may work well at a higher or lower SOUR. However, they would normally mean that one should begin looking for potential problems.

The fed and unfed tests use the simple OUR test on simulated sludges. A “fake” activated sludge is developed to simulate conditions at the influent end of the aeration tank. It is a “fake” test because of the difficulty of collecting a truly mixed sample at that point. Since the results of the tests must relate to each other, the unfed test uses the same organisms for a “fake” test to simulate the conditions at the effluent end of the aeration tank. The unfed test indicates how active the microorganisms are at rest (endogenous respiration conditions) while the fed test shows the microorganism activity after feeding.

The fed test mixes the correct amount of influent with an amount of return activated sludge to simulate the MLSS concentration in the aeration tank. The unfed test mixes unchlorinated final effluent with the RAS to achieve the same MLSS concentration. The normal OUR test is then done on each sample. The correct volume of RAS in mL is calculated by:

$$\text{mL of RAS} = \frac{\text{MLSS in Aeration Tank} \times 300 \text{ mL}}{\text{MLSS of RAS}}$$

Once the two tests have been completed, a ratio of the fed to unfed OUR is calculated. If the ratio is less than 1.0, there is probably some toxic material in the influent, because the bugs in the fed sample should be using oxygen at a higher rate than the bugs in the unfed sample. A value of 1.0 to 2.0 is found with very dilute influent samples or waste that contains slowly degradable materials. A ratio of 2.0 to 5.0 is normal for domestic wastewater, while a ratio of greater than 5.0 indicates extremely high loading.

#### Fed/Unfed Ratios for Domestic Wastewater

- <1.0 → Toxic effect
- 1.0 – 2.0 → Dilute load or hard to stabilize material
- 2.0 – 5.0 → Normal
- >5.0 → Very high organic load for the MLSS available



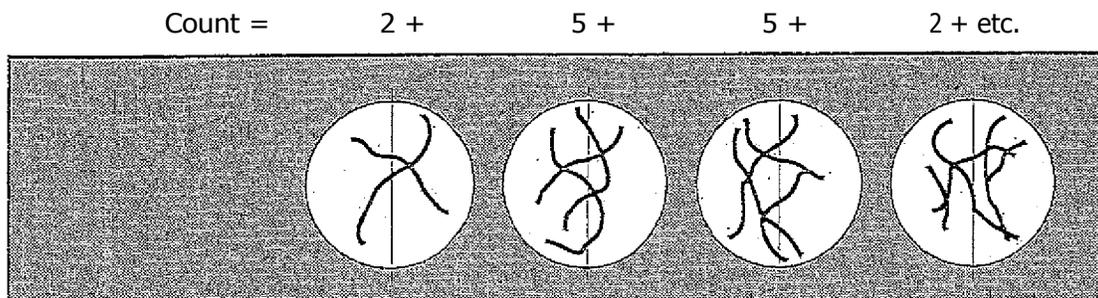
APPENDIX I  
MICROSCOPIC TEST PROCEDURES

### *Procedures for Microscopic Examination*

Use a sample of mixed liquor from the aeration basin for microscopic examination as part of the routine daily lab tests.

1. Take an eye dropper full of mixed liquor from the aeration basin, place one drop onto a slide, place a cover slip on the top of the drop. Take care to exclude air bubbles.
2. Using 100x power (10x eyepiece plus the 10x objective) on the microscope, start the field of view on one edge of the slide and note on the worksheet the number of different microorganisms listed that are in view.
3. Proceed across the slide with a new field of view each time on the edge of the preceding one. Repeat this ten times, then add up the total numbers on the worksheet and record the relative predominance.
4. When counting stalked ciliates, count each single stalk as one; Therefore a dump of stalks could be counted as being ten or more stalked ciliates.
5. When counting filaments, add the number of times a filament crosses over an imaginary vertical line drawn through the field of view. Refer to the diagram at the bottom of the page for an example.
6. After viewing the ten areas that were counted and recorded, view the whole slide and note any additional information that you feel is important.

#### **Filament Counting Technique**



## Worksheet for Microscopic Examination of Activated Sludge

Date: \_\_\_\_\_ Time: \_\_\_\_\_ By: \_\_\_\_\_

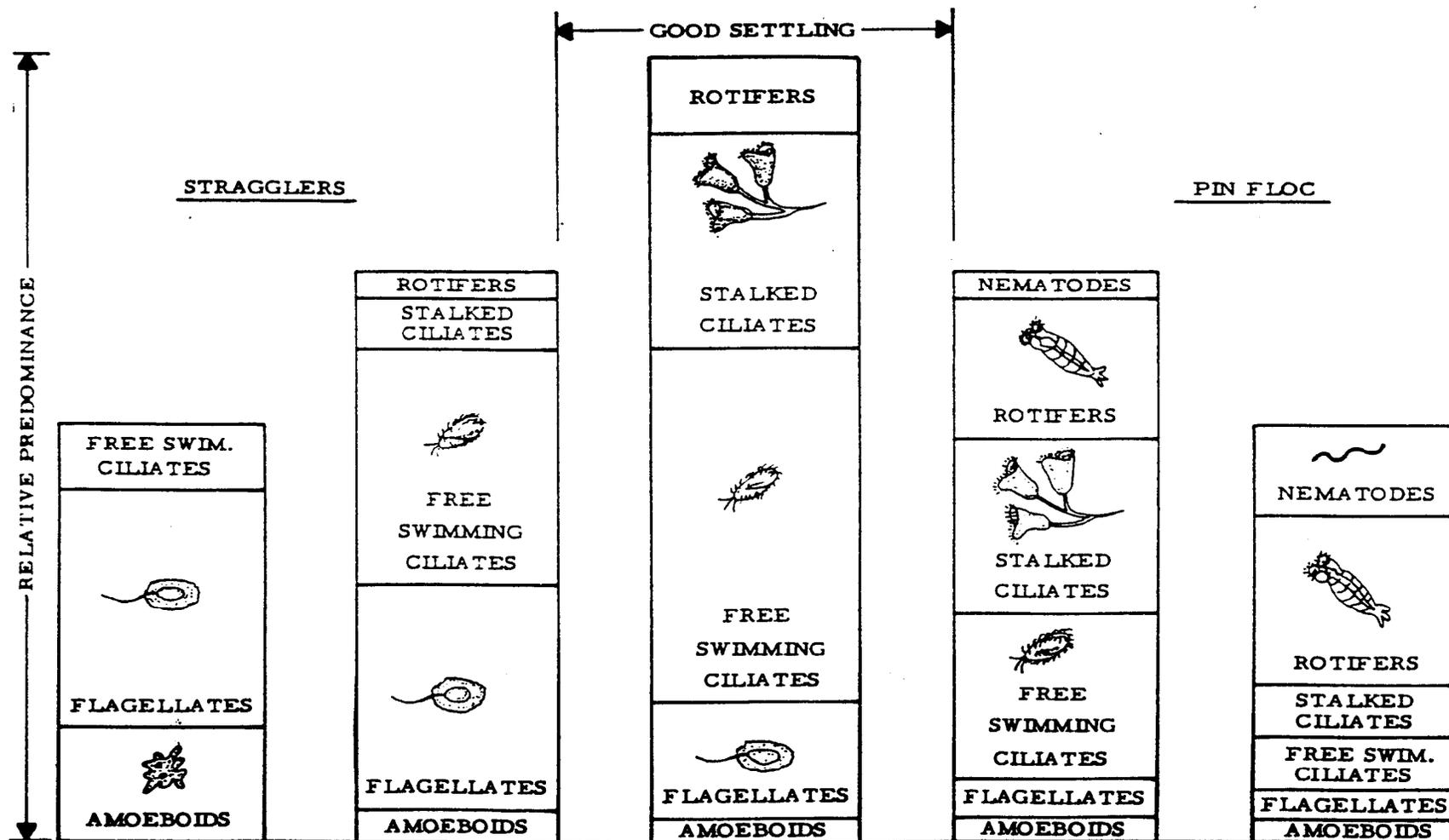
Sample Location: \_\_\_\_\_

| Microorganisms   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Total |
|--|---|---|---|---|---|---|---|---|---|----|-------|
| Amoeboids               |   |   |   |   |   |   |   |   |   |    |       |
| Flagellates             |   |   |   |   |   |   |   |   |   |    |       |
| Free Swimming Ciliates  |   |   |   |   |   |   |   |   |   |    |       |
| Stalked Ciliates        |   |   |   |   |   |   |   |   |   |    |       |
| Rotifers                |   |   |   |   |   |   |   |   |   |    |       |
| Filaments  |   |   |   |   |   |   |   |   |   |    |       |
| Other  |   |   |   |   |   |   |   |   |   |    |       |

Relative Predominance:      Observation:

|    |  |
|----|--|
| 1. |  |
| 2. |  |
| 3. |  |
| 4. |  |
| 5. |  |

# MICROSCOPIC EXAM



RELATIVE NUMBER OF MICROORGANISMS VS. SLUDGE QUALITY

APPENDIX J

ACTIVATED SLUDGE OBSERVATIONS

### Activated Sludge Observations

|                         | MON | TUE | WED | THU | FRI | SAT | SUN |
|-------------------------|-----|-----|-----|-----|-----|-----|-----|
| Aeration Tank           |     |     |     |     |     |     |     |
| Color of the Sludge     |     |     |     |     |     |     |     |
| Color of Foam           |     |     |     |     |     |     |     |
| Characteristics of Foam |     |     |     |     |     |     |     |
| Odor                    |     |     |     |     |     |     |     |
| Comments                |     |     |     |     |     |     |     |
| Final Clarifiers        |     |     |     |     |     |     |     |
| Color                   |     |     |     |     |     |     |     |
| Clarity                 |     |     |     |     |     |     |     |
| Appearance              |     |     |     |     |     |     |     |
| Bulking                 |     |     |     |     |     |     |     |
| Solids Washout          |     |     |     |     |     |     |     |
| Clumping                |     |     |     |     |     |     |     |
| Ashing                  |     |     |     |     |     |     |     |
| Straggler Floc          |     |     |     |     |     |     |     |
| Pin Floc                |     |     |     |     |     |     |     |
| Comments                |     |     |     |     |     |     |     |

APPENDIX K  
ORP Ranges (mV)

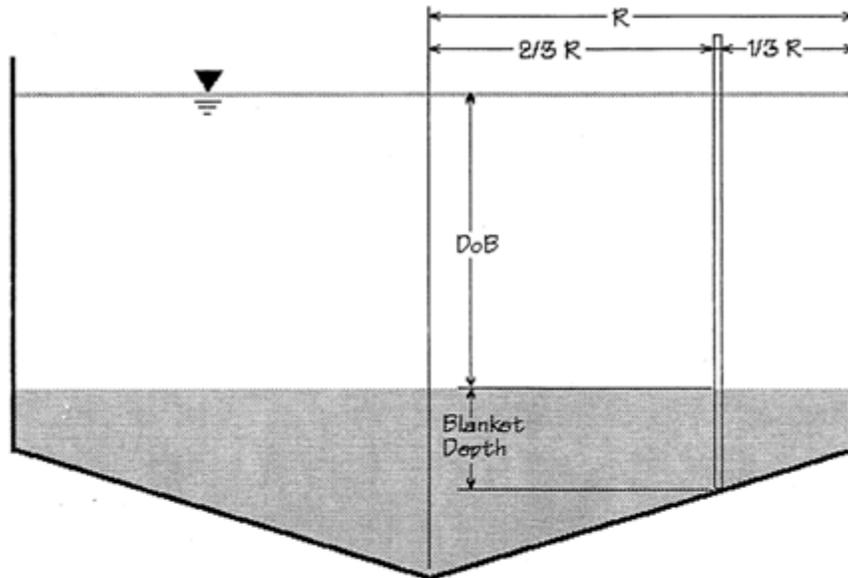
# ORP Ranges (mV)

| ORP     |   | Electron Acceptors | Conditions         |
|---------|---|--------------------|--------------------|
| +200 mv | 1 | $O_2$              | Oxic or<br>Aerobic |
| +100 mv |   |                    |                    |
| 0 mv    | 2 | $NO_3^-$           | Anoxic             |
| -100 mv | 3 | $SO_4^{2-}$        | Anaerobic          |
| -200 mv |   |                    |                    |

1 - Nitrification      3 - Sulfide Formation  
 2 - Denitrification    4 - Organic Acid Formation

\

APPENDIX L  
CORE TAKER PROCEDURES



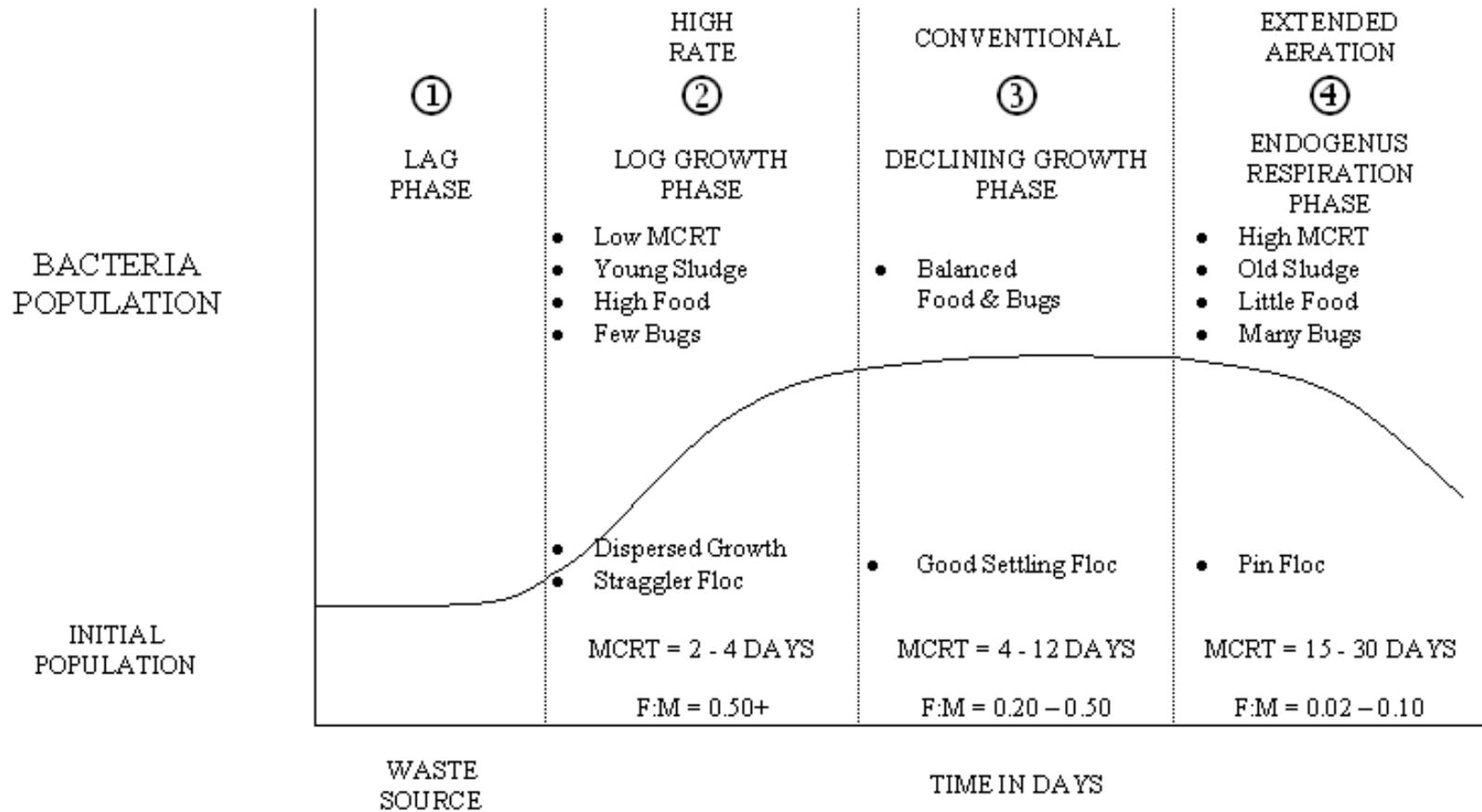
1. Use a core-taker (Sludge Judge).
2. Always use the same sample location -  $1/3$  of the clarifier radius in from the outside wall in circular clarifiers,  $1/2$  the length of the clarifier for rectangular clarifiers.
3. Always sample at the same time of day.
4. Sample when the scraper is approximately  $90^\circ$  away from the sample location.
5. Lower the core-taker *slowly* to the bottom of the tank.
6. With a slight tug to set the ball-valve, lift the core-taker straight up.
7. Measure the Blanket Depth and Depth of Blanket ( $DoB$ ) to the nearest  $1/10$  foot
8. Empty the core-taker into a clean container to use to determine clarifier solids concentration.



APPENDIX M

MCRT RELATIONSHIP TO F/M  
(Source – Bill Olver, P.E.)

# MCRT RELATIONSHIP TO F:M RATIO



APPENDIX N

FINAL CLARIFIER SOLIDS FLUX

(Source: Bill Olver, P.E.)

FINAL CLARIFIER SOLIDS FLUX IS OFTEN THE CAUSE OF POOR PROCESS PERFORMANCE

$$\text{SOLIDS FLUX} = \frac{\text{SOLIDS APPLIED TO CLARIFIER (LBS/DAY)}}{\text{CLARIFIER AREA (SF)}}$$

$$\text{SOLIDS FLUX} = \frac{(\text{INFLUENT FLOW} - \text{RAS FLOW})_{\text{MGD}} \times \text{MLSS}_{\text{mg/L}} \times 8.34}{\text{CLARIFIER AREA (SF)}}$$

- MAXIMUM SOLIDS FLUX FOR TYPICAL MUNICIPAL MLSS:
  - AT AVERAGE DAILY FLOWS – 24 LBS/DAY/SF
  - AT PEAK HOURLY FLOWS – 48 LBS/DAY/SF

APPENDIX O  
Troubleshooting Charts

## Aeration Problems

| Observation   | Probable Cause                              | Check   | Alternatives   |
|---|---|---|--|
| 1. For diffused air systems boiling action, violent turbulence throughout aeration tank surface. Large air bubbles, 1/2 inch or greater. For mechanical aeration systems, violent turbulence. | A. Overaeration resulting in high DO and/or | 1. Check DO, should be in range of 1.0 to 3.0 mg/l throughout tank.                                   | 1. Reduce aeration to maintain DO in proper range.<br>a. If diffused air, lower air flow rate.<br>b. If mechanical, reduce aerator speed or lower aeration tank weir.  |
| 2. For diffused air systems, uneven surface aeration pattern. Dead spots or inadequate mixing. For mechanical aeration, inadequate mixing.  | A. Clogged diffusers floc shearing.         | 1. Check maintenance records for last cleaning of diffusers.<br>2. Check diffusers for clogging       | 1. If diffusers have not been cleaned in the last, 12 months, do so.<br>2. If several are clogged, clean all diffusers.  |
|   | B. Leaks in air piping.                     | 1. Check air- pipe and joints; listen for air leakage or soap test and watch for bubbling.            | 1. Tighten flange bolts and/or replace flange gaskets.   |
|   | C. Imbalance with diffuser header valves.   | 1. Check valve adjustment.  | 1. Balance valves as required.   |
|   | D. Air flow to low.                         | 1. Check air flow.  | 1. Increase air flow.  |
|   | E. Problems with blower.                    | 1. Check the blower. PM required, service record, design and present output.                          | 1. Repair as required.   |
|   | F. Aerator speed too low.                   | 1. Check aerator speed.   | 1. Increase aerator speed.   |
|   | G. Impeller submergence too little          | 1. Check impeller submergence   | 1. Increase submergence by raising weir or lowering impeller.  |
|   | H. Rag or ice fouled aerator blades.        | 1. Check blades for rags or ice.  | 1. Remove rags or ice.   |
| 3. Low DO and/or septic odors in mixed liquor.  | A. Underaeration.                           | 1. Check DO, should be in range of 1.0 to 3.0 mg/t.<br>2. Check for adequate mixing in aeration tank. | 1. Increase aeration.<br><br>2a. For diffused air systems, calculate air flow rate per unit length of diffuser header pipe. Minimum required is 3 scfm/lin. ft. Adjust air flow rate as necessary to maintain adequate DO end mixing.<br><br>2b. For mechanical aeration, increase mixing by increasing aerator speed or raising aerator tank weirs. |

## Aeration Problems - Continued

| Observation   | Probable Cause   | Check   | Alternatives   |
|---|--|---|--|
|   |  | 3. Check return rate and sludge blanket depth in clarifier  | 3. Adjust return rate to maintain sludge blanket depth of 1 to 2 feet in clarifier.  |
|   | B. MLSS may be too high  | 1. Check MLSS.  | 1. Adjust MLSS for proper F/M.<br>2. If proper F/M, put additional aeration tanks on-line if possible.   |
| 4. Excessive aeration needed although no apparent change in organic or hydraulic loading Difficult to maintain adequate DO level. | A. If diffused air system, leaks in air piping.  | 1. Check air pipe and joints; listen for air leakage or soap test and watch for bubbling.   | 1. Tighten flange bolts and/or replace flange gaskets.   |
|   | B. If diffused air system, clogged diffusers. Air discharging from diffuser header blow-off pipes causing local boiling to occur on surface near diffuser header pipe. | 1. Check maintenance record for last cleaning of diffusers.<br>2. Check diffusers in tank for clogging.   | 1. If diffusers have not been cleaned in last 12 months, do so<br>2. If several are clogged, clean all diffusers.  |
|   | C. If mechanical aerator, blades fouled with rags or ice.  | 1; Check blades for rags or ice.  | 1. Remove rags or ice  |
|   | D. Insufficient or inadequate oxygen transfer.   | 1. Check aeration system performance.<br>a. Diffused aeration~ system should provide air between 750 to 2000 cu ft/lb BOD removed.<br>b. Mechanical aeration systems should provide between 1 to 1.5 lb/lb BOD removed. | 1. Replace with more effective diffusers or mechanical aerators.<br>2. Add more diffusers or mechanical aerators.  |
|   | E. High organic loadings from in-plant sidestream flows.   | 1. Check if organic loading from sidestream flows contributes significantly to overall process loading.   | 1. If loadings are greater than 15% optimize operational performance or upgrade other in-plant processes.  |
| 5. Difficult to maintain DO level at head end of aeration tank.   | A. Influent organic load being improperly distributed to aeration tanks.   | 1. Check if DO too low at head end but adequate elsewhere   | 1. If possible, change influent points from plug flow to step feed or complete mix   |
|   | B. If diffused air system air being improperly distributed   | 1. Check' air distribution.   | 1. If possible, redistribute air.<br>2. If, necessary, consider changing diffuser layout.  |
| 6. Surging of the water surface with oscillating wave pattern caused by mechanical aeration equipment                             | A. Inadequate impeller submergence.  | 1. Check manufacturer's recommendation for minimum submergence  | 1. Raise or shorten aeration tank weir.<br>2. Lower impeller.<br>3. Reduce aeration tankage on-line if otherwise impossible, to raise the water surface.<br>4. Consider experimenting with baffles, draft tubes, etc.<br>5. Check the aeration tank weir for leaks.<br>6. Increase the return rate as a last resort, |

## Foaming Problems

| Observation   | Probable Cause  | Check  | Alternatives   |
|---|---|--|--|
| 1. Stiff, white billowing or sudsy foam on aeration tank surface. | A. Young sludge in an overloaded aeration tank (low MLSS) Note: This problem usually occurs during process start-up and is only temporary. If start-up, do not be alarmed by it.  | 1. Check aeration tank BOD loading (lb/day) and lb MLVSS in aeration tank. Include BOD load from any recycled in-plant side streams such as digester supernatant, filtrate, etc. that are on-line. Calculate the FIM to determine MLVSS inventory for current BOD loading. | 1. After calculating the FIM and lb MLVSS needed, you may find that the F/M is high and the lb MLVSS inventory is low. Therefore, do not waste sludge from the system for a few days or maintain the minimum wasting rate possible if wasting has already started. |
|   |   | 2. Check secondary clarifier effluent for solids carryover. Effluent will look cloudy.   | 2. Maintain sufficient return rates to minimize solids carryover, especially during peak flow periods. Washing out solids reduces solids inventory and increases F/M   |
|   |   | 3. Check DO levels in aeration tank.   | 3. Try to maintain DO levels between 1.0 to 3.0 mg/l. Also be sure that adequate mixing is being provided in the aeration tank while attempting to maintain the DO.  |
|   | B. Excessive sludge wasting from process causing overloaded aeration tank (low MLSS)  | 4. Consider hauling in seed activated sludge from another plant  | 4. Seed the process with healthy activated sludge from a well operating plant.   |
|   |   | 1. Check and monitor trends for: <ol style="list-style-type: none"> <li>Decreasing MLVSS, mg/l</li> <li>Decreasing SRT</li> <li>Increasing f/M</li> <li>Decreasing aeration for the same DO levels.</li> <li>Increasing wasting rates.</li> </ol>                          | 1. Reduce wasting rate by not more than 10-15 percent per day until process approaches normal operation. Increase return rate to minimize effluent carryover. Maintain sludge blanket depth of 1 to 2 feet.  |
|   | C. Unfavorable conditions such as highly toxic waste (metals or bactericide), nutrient deficiency, abnormally low or high pH, insufficient DO, colder wastewater temperatures. or severe temperature variations resulting in reduction of MLSS. | 1. Check respiration rate. Toxic upset likely if OUR extremely low (less than 5mg/g h). Take MLSS sample and test for metals, bactericide and temperature.   | 1. Re-establish new culture of activated sludge. If possible, waste toxic sludge from the process without recycling portions of it back into process. Obtain seed sludge from other plant, if possible. Actively enforce sewer use ordinance.                      |
|   |   | 2. Check plant influent for significant variations in temperature.   | 2. Actively enforce sewer use ordinance.   |

## Foaming Problems - Continued

| Observation  | Probable Cause   | Check  | Alternatives   |
|--|--|--|--|
|  | D. Unintentional loss of biomass such as hydraulic washout of solids from secondary clarifier reducing MLSS and causing aerat i on' tank overload. | 1. Check surface overflow rate in secondary clarifier.   | 1. Refer to solids washout observation No.1 and clumping/rising sludge cause 1A.   |
|  | E. Improper influent wastewater and/or RAS flow distribution causing overloading and thereby foaming.  | 1. Check and monitor secondary influent and return rates to each aeration' tank. Differences may cause significant differences in MLSS concentrations.   | 1. Modify distribution facilities as necessary to equalize influent wastewater and return rates. MLSS and RAS concentrations and DOs between multiple tanks should be reasonably consistent.   |
| 2. Shiny, dark brown foam on aeration tank surface.                        | A. Aeration tank approaching underloaded (low f/M) conditions due to insufficient sludge wasting   | 1. Check and monitor trends for:<br>a. Increasing MLVSS, mg/l.<br>b. Increasing SRT.<br>c. Decreasing f/M.<br>d. Increasing aeration for the same DO level.<br>e. Decreasing WAS rates.<br>f. Increasing temperatures.<br>2. Check and monitor secondary influent and return rate to each aeration tank. Imbalance may be overloading one tank.  | 1. Increase wasting rate by not more than 10 - 15 percent per day until process approaches normal operations and a modest amount of light tan foam is observed on aeration tank surface<br>2. Equalize influent and return rates to each aeration tank.    |
| 3. Thick, scummy dark brown foam on aeration tank surface.                 | foam A. Aeration tank is critically underloaded (f/M too low) due to improper wasting program.   | 1. Check and monitor trends for:<br>a. Increasing MLVSS, mg/l.<br>b. Increasing SRT.<br>c. Decreasing f/M.<br>d. Increasing aeration for the same DO level.<br>e. Decreasing WAS rates.<br>f. Increasing temperatures.<br>1. Check and monitor secondary influent and return rate to each aeration tank. Imbalance may be underloading one tank. | 1. Increase wasting rate by not more than 10 - 15 percent per day until process approaches normal operations and a' modest, amount of light tan foam is observed on aeration tank surface.<br>1. Equalize influent and return rates to each aeration tank. |
|  | B. Scum entering aeration tanks.   | 1. Check:<br>a. Secondary influent for oil & grease.<br>b. Primary scum collection system.   | 1a. Enforce sewer use<br>b. Improve primary scum capture.ordinance.  |
| 4. Greasy, dark tan foam that is strong and carries over to the clarifier. | A. filamentous organism (Nocardia or Microthrix).  | 1. Check results of microscopic exam of mixed liquor   | 1. Refer to Bulking observation No. 2  |

## Foaming Problems - Continued

---

| Observation   | Probable Cause   | Check                                 | Alternatives                    |
|---|--|---------------------------------------|---------------------------------|
| 5. Dark-brown, almost blackish sudsy foam on aeration tank surface. Mixed liquor color is very dark brown almost black. Septic or sour odor from aeration tank. | A. Anaerobic conditions in aeration tank.                        | 1. Refer to aeration problems.        |                                 |
|   | B. Industrial waste containing dyes or ink:                      | 1. Check sources of industrial waste. | 1. Enforce sewer use ordinance. |
| 6. Modest amount of fresh light tan foam.   | A. Not a problem. Usually a sign of a well operated process good |                                       |                                 |

## Solids Washout

| Observation  | Probable Cause   | Check  | Alternatives  |
|--|--|--|---|
| 1. Localized clouds of homogenous sludge solids rising in certain areas of the clarifier. Mixed Liquor in settleability test settles fairly well with a clear supernatant. | A. Equipment malfunctions.   | 1. Check the following equipment for abnormal operation. <ol style="list-style-type: none"> <li>Flow meter for calibration.</li> <li>RAS or \.LAS pumps and transfer Lines for plugging.</li> <li>Sludge collection equipment for such things as~ broken or worn out flights or drives, chains, sprocket, squeegees, and plugged sludge withdrawal tubes.</li> <li>Clarifier inlet or outlet baffles and skirts for damage.</li> <li>Weirs for level.</li> </ol> | 1. Repair or replace abnormal operating equipment. <ol style="list-style-type: none"> <li>Recalibrate flow meter.</li> <li>Unplug pumps or Lines.</li> <li>Repair collector. [f plugged sludge withdrawal tubes, back flush submerged manifold and orifices. of collection system.</li> <li>Repair or replace damaged baffles.</li> <li>Level weirs.</li> </ol> |
|  |  | 2. Check sludge removal rate and sludge blanket depth in clarifier.  | 2. Adjust return rates and sludge collector mechanism speed if possible to maintain sludge blanket depth at 1 to 2 ft.  |
|  | B. Air or gas trapped in sludge floc or denitrification occurring. | 1. Perform mixed liquor settleability test. Gently stir sludge when settling to see if bubbles are released. <ol style="list-style-type: none"> <li>If bubbles are released, check nitrate concentration in secondary to see if nitrification is occurring.</li> <li>If bubbles are not released, the process is not nitrifying.</li> </ol>  | 1. From test results: <ol style="list-style-type: none"> <li>If process is nitrifying, refer to clumping/rising sludge cause 1A.</li> <li>If process not nitrifying refer to Cause A above and, ashing, pinpoint floc and straggler floc cause 2B.</li> </ol>   |
|  | C. Temperature currents.   | 1. Check temperature throughout clarifier using a temperature profile.   | 1. If temperature differences exceed 2 to 4 F between top and bottom of clarifier, take a clarifier offline if possible.  |
|  |  | 2. Check inlet and outlet baffling for proper solids distribution in clarifier   | 2. Modify or install additional baffling in clarifier.  |
|  | D. Hydraulic or solids overloading.                                | 1. Check for equal flow distribution to each aeration tank and clarifier.  | 1. Equal flow by adjusting weirs, valves, etc.  |
|  |  | 2. Check surface overflow rate in clarifier for average and peak flow.   | 2. If overflows rate exceeds design capability, use additional clarifiers if possible.  |

## Solids Washout - Continued

| Observation | Probable Cause | Check   | Alternatives   |
|-------------|----------------|---|--|
|             |                | 3. Check clarifier solids loading.                        | 3. ' If solids loading is too high: ut another clarifier on-Line, if possible; put another aeration tank on-line, if possible, lower MLSS for the, same F/M or waste sludge.   |
|             |                | 4. Check ISV, and calculate minimum return.               | 4a. Make step feed change, if possible, or increase wasting rate' if not b. Increase return if indicated.  |
|             |                | 5. Check clarifier sludge blanket.                        | 5. If solids loading are OK but blanket is too high, increase return rate and, if possible, move feed towards contact stabilization to transfer solids from clarifier to aeration tank. Increase wasting if SRT is too high. |
|             |                | 6. Check the area around the clarifier for excessive wind | 6. Provide a wind screen if clarifier is large.  |
|             |                | 7. Check process mode.                                    | 7. If possible, change process operation to sludge reaeration or contact stabilization mode.   |
|             |                | 8. Check results of jar test.                             | 8. Add polymer or alum as a temporary measure.   |
|             |                | 9. Check for excessive inflow/infiltration.               | 9. Set up an I/I reduction program.  |

## Bulking sludge

| Observation  | Probable Cause   | Check   | Alternatives   |
|--|--|---|--|
| <p>1. Clouds of billowing homogenous sludge rising and extending throughout the clarifier. Mixed liquor settles slowly and compacts poorly in settleability test, but supernatant is fairly clear. Microscopic exam shows few or no filamentous organisms. Sudden increase in SVI.</p> | A. Improper organic loading causing dispersed growth bulking.    | <p>1. Check and monitor trends for:</p> <ul style="list-style-type: none"> <li>a. Changing MLVSS, mg/l.</li> <li>b. Changing SRT.</li> <li>c. Changing F/M.</li> <li>d. Changing DO levels.</li> <li>e. Changing influent BOD.</li> </ul> | <ul style="list-style-type: none"> <li>1. Adjust wasting rates by not more than 10 to 15 percent per day until process approaches normal operations.</li> <li>2. Temporarily increase return rates to minimize solids carryover from clarifier. Continue until normal control parameters are approached.</li> </ul>  |
|  | B. Too high DO level causing dispersed growth bulking.           | <ul style="list-style-type: none"> <li>1. Check for increasing DO levels.</li> </ul>  | <ul style="list-style-type: none"> <li>1. Decrease DO level, preferably to 1.0 to 3.0 mg/l.</li> </ul>   |
|  | C. Taxies present causing dispersed growth bulking.              | <ul style="list-style-type: none"> <li>1. Check mixed liquor respiration rate.</li> </ul>   | <ul style="list-style-type: none"> <li>1. Enforce sewer use ordinance. Note: Chlorine is ineffective in correcting dispersed growth bulking.</li> </ul>  |
| <p>2. Same as above except microscopic exam shows numerous filaments. Note: Try to identify filaments.</p>   | A. Wastewater nutrient deficiencies causing filamentous bulking. | <ul style="list-style-type: none"> <li>1. Check nutrient levels in influent wastewater.</li> <li>2. Check settleability with mixed liquor settleability test.</li> </ul>  | <ul style="list-style-type: none"> <li>1. If nutrient levels are Less than average ratio, perform field test on the influent wastewater to find dosages for adding nitrogen, phosphorus and iron.</li> <li>2. Observe test for improvement in sludge settling characteristics with nutrient addition.</li> <li>3. Chlorinate RAS at 2 to 3 lb/day per 1000 lb MLVSS.</li> <li>4. Add a settling aid, if possible, to relieve symptoms while underlying problem is being corrected.</li> </ul>                          |
|  | B. Low DO in aeration tank causing filamentous bulking.          | <ul style="list-style-type: none"> <li>1. Check DO at various location throughout the aeration tank.</li> </ul>   | <ul style="list-style-type: none"> <li>1. If average DO is less than 0.5 mg/l, increase aeration until the DO increase to between 1.0 and 3.0 mg/l throughout the tank</li> <li>2. If DO is nearly zero in some parts of the tank, but 1 mg/l in other locations: <ul style="list-style-type: none"> <li>a. For diffused aeration, balance the air distribution system or clean diffusers.</li> <li>b. For mechanical aeration, increase aerator speed if possible or raise the overflow weirs.</li> </ul> </li> </ul> |

## Bulking sludge

| Observation  | Probable Cause  | Check   | Alternatives  |
|--|---|---|---|
|  | B. Low DO in aeration tank causing filamentous bulking.   | 1. Check DO at various location throughout the aeration tank.   | <ol style="list-style-type: none"> <li>If DO is low only at the head of the tanks which are being operated in the plug flow pattern, change to step feed or complete mix flow pattern or change to tapered aeration</li> <li>Chlorinate RAS at 2 to 3 lb/day 1000 lb HLVSS.</li> <li>Add a settling aid, if possible to relieve systems while underlying problem is being corrected.</li> </ol>   |
|  | C. Wide fluctuations in raw wastewater pH or aeration tank pH less than 6.5, causing filamentous bulking.   | <ol style="list-style-type: none"> <li>Check and monitor plant influent pH.</li> <li>Check if process is nitrifying due to warm wastewater temperature or low F/M.</li> </ol> | <ol style="list-style-type: none"> <li>If pH is less than 6.5, conduct industrial waste survey to identify source. If possible, stop or have discharge neutralized at source.</li> <li>If the above is not possible, raise pH by adding an alkaline such as sodium bicarbonate or lime to the aeration tank influent.</li> <li>If nitrification is not required, increase wasting rate by not more than 10 - 15 percent per day to stop nitrification.</li> <li>If nitrification is required raise pH by adding an alkaline such as sodium bicarbonate or lime to the aeration tank influent.</li> <li>Chlorinate RAS at 2 to 3 lb/day/load lb MLVSS.</li> <li>Add a settling aid, if possible, to relieve the symptoms while the underlying problem is corrected.</li> </ol> |
|  | D. Massive amounts of bacteria filaments in influent wastewater or in-plant side stream are causing filamentous bulking in the activated sludge process | <ol style="list-style-type: none"> <li>Check influent wastewater for filaments.</li> <li>Check in-plant sidestream for filaments.</li> </ol>                                  | <ol style="list-style-type: none"> <li>Chlorinate influent at 5 to 10 mg/l dosages. If higher doses are required use extreme caution. Increase the dosage at 1 to 2 mg/l increment.</li> <li>Optimize performance of other in-plant processes. Upgrade in-plant process</li> </ol>  |
|  | E. Insufficient soluble BOD causing low F/M bulking.  | 1. Check soluble BOD throughout aeration tank.  | 1. Consider changing to step feed or plug flow if possible.   |
| <p>Note: Filamentous conditions will reoccur if underlying nutrient, DO, or pH problem is not corrected.</p> |   |   |   |

## Clumping/Rising sludge

| Observation   | Probable Cause                       | Check  | Alternatives  |
|---|--------------------------------------|--|---|
| <p>1. Sludge clumps (from size of a golf ball to as large as a basketball) rising and dispersing on clarifier surface. Bubbles noticed on clarifier surface. Mixed liquor in settleability test settles fairly well. However, a portion of, or all of the settled sludge rises to the surface within two hours after the test started</p> | A. Denitrification in clarifier.     | <p>1. Check for increase in secondary effluent nitrate level.</p> <p>2. Check for increasing SRT and decreasing f/M</p> <p>3. Check DO levels in the aeration tank.</p> <p>4. Check return rates and sludge blanket depth in clarifier.</p> <p>5. Check clarifier for proper mechanical operation.</p> <p>6. Check and evaluate number of clarifiers required on-line.</p> | <p>1. If nitrification is not required, gradually increase wasting rate to reduce or eliminate nitrification. If nitrification is required, reduce to allowable minimum.</p> <p>2a. Gradually increase wasting rates to keep process within proper SRT and F/M, especially during hot weather when SRT should be decreased.</p> <p>b. Decrease wasting rates to be sure nitrification is complete and soluble BOD is low.</p> <p>3. Increase DO to provide oxygen throughout sludge blanket.</p> <p>4. Increase RAS rate to maintain sludge blanket level of 1 to 2 feet in clarifier.</p> <p>5. Clean suction tubes if plugged.</p> <p>6. Reduce the number of clarifiers on-line to shorten the detention time.</p> |
|   | B. Septicity occurring in clarifier. | <p>1. Refer to aeration problem observation No.3.</p> <p>2. See 3 and 4 above.</p> <p>3. Check for mechanical problems in clarifier such as;</p> <p>a. Broken or warped wooden flights.</p> <p>b. Clogged sludge withdrawal tubes.</p>   | <p>3. Perform needed maintenance.</p> <p>a. Repair or replace damaged flights.</p> <p>b. Jet tubes with air or water.</p>   |

## Cloudy Secondary Effluent

| Observation  | Probable Cause   | Check   | Alternatives   |
|--|--|---|--|
| 1. Secondary effluent from clarifier is cloudy and contains suspended matter. Mixed liquor in settleability test settles poorly, leaving a cloudy supernatant. | A. MLSS in aeration tanks low due to process start-up. | 1. Refer to foaming problems cause 1A.  |  |
|  |  | 1. Examine mixed liquor and return sludge with microscope. Check for presence and condition of protozoa.<br><br>2. Check organic loading (F/M) in process. Include BOD load from recycled in-plant streams such as digester supernatant, filtrate etc.<br><br>3. Check DO in aeration tank. | 1a. If few or no protozoa are present, possible shock organic loading has occurred.<br>b. If there are a large number of flagellates or amoebae, the system may be overloaded.<br><br>2. If F/M higher than normal, reduce wasting rate by not more than 10 to 15 percent per day to bring process back to proper loading and increase return rate to lower blanket to minimum to transfer solids' to aeration tank.<br><br>3. Adjust aeration rate to maintain DO within 1.0 to 3.0 mg/L.<br><br>4. Add a settling aid such as alum, ferric chloride, or polymer to help settle floc. |
|  | c. Toxic shock loading.                                | 1. Examine mixed liquor and return sludge under microscope, Check for presence and condition of protozoa.<br><br>2. Check mixed liquor respiration rate for sudden decrease.  | 1a. If protozoa are present but inactive, possibility of recent, toxic load on process. Reduce wasting but otherwise maintain normal operation.<br>b. If few or no protozoa are present and DO is adequate, toxic load to process. If toxics are still present in the system, continue normal wasting or even increase wasting from the system to purge the system. If toxics have already passed through the system, get seed sludge and stop wasting until microorganisms build up.<br><br>2. If less than 5 mg/g-h, toxic shock likely.   |

## Cloudy Secondary Effluent - Continued

| Observation | Probable Cause                                      | Check   | Alternatives  |
|-------------|---|---|---|
|             |   | 3. Check composite influent sample and/or mixed liquor for toxics.  | 3. If metals are present in the mixed liquor, consider increasing the wasting for a week or so to purge the system. Also, try to trace toxics back to industrial source or "septic" tank truck discharge. |
|             | D. Overaeration causing mixed liquor floc to shear. | 1. Examine mixed liquor with microscope. Check for dispersed or fragmented floc and presence and condition of protozoa. | 1. If protozoa are active and healthy and the floc is dispersed, refer to aeration problems observation No.1.   |
|             | E. Low DO in aeration tanks.                        | 1. Examine mixed liquor under microscope for presence and condition of protozoa, check F/M and DO.                      | 1. If few or no protozoa, F/M lower than or within normal range, and DO low, refer to aeration problem observations No.2 and 3.   |

## Ashing, pinpoint floc, and straggler floc

| Observation  | Probable Cause   | Check   | Alternatives   |
|--|--|---|--|
| 1 Fine dispersed floc (about the size of a pinhead) extending throughout the clarifier with little islands of sludge accumulated on the surface and discharging over the weirs. Mixed liquor in settleability test settles fairly well. Sludge is dense at bottom with fine particles of floc suspended in fairly clear supernatant (pinpoint floc). | A. Aeration tank approach underloaded conditions (low F/M) because of old sludge.  | <ol style="list-style-type: none"> <li>1. Check and monitor trends for:               <ol style="list-style-type: none"> <li>a. Increasing MLVSS, mg/l.</li> <li>b. Increasing SRT.</li> <li>c. Decreasing F/M.</li> <li>d. Increasing aeration for the same DO Levels.</li> <li>e. Decreasing wasting.</li> <li>f. Decreasing organic load (BOD or COD) in secondary influent.</li> </ol> </li> <li>2. Check for proper aeration and mixing in aeration tank.</li> </ol>   | <ol style="list-style-type: none"> <li>1. Increase wasting rates by not more than 10 to 15 percent per day to bring back to optimum control. If nitrification is required, avoid wasting too much.</li> <li>2. Refer to aeration problems.</li> <li>3. Add a settling aid such as alum, ferric chloride or polymer if possible to help settle floc.</li> </ol>   |
| 2. Small particles of ash-like material floating on surface of clarifier and in mixed liquor settleability test(ashing).   | <p>A. Beginning of denitrification.</p> <p>B. Excessive amounts of grease in mixed liquor.</p> <p>C. F/M extremely low and beyond extended aeration range (less than 0.05)</p> | <ol style="list-style-type: none"> <li>1. Check settleability. Stir floating floc on surface of 30"min settleability test.</li> <li>1. Check grease analysis of MLSS, and check scum baffles and scum removal system in primary tank.</li> <li>2. Check grease content in raw wastewater.</li> <li>1. Check and monitor trends for:               <ol style="list-style-type: none"> <li>a. Increasing MLVSS, mg/l.</li> <li>b. Increasing SRT.</li> <li>c. Decreasing F/M.</li> <li>d. Increasing aeration for the same DO levels.</li> <li>e. Decreasing wasting rates.</li> <li>f. Decreasing organic load (BOD or COD) in secondary influent.</li> </ol> </li> <li>2. Check mixed liquor settleability.</li> <li>3. Check for small thin amounts of scum on clarifier surface.</li> </ol> | <ol style="list-style-type: none"> <li>1. If floating floc releases bubbles and settles, see clumping/rising sludge cause 1A.</li> <li>2. If it does not settle, see causes Band C below.</li> <li>1. If the grease content exceeds 5% by weight of the MLSS, repair or replace scum baffles, as needed or improve operation of scum removal.</li> <li>2. If grease content is excessive, conduct industrial waste survey and enforce sewer use ordinance.</li> <li>1. If ashing is significant enough to impact effluent quality by increasing effluent suspended solids, increase the wasting by not more than 10 to 15 percent per day to raise the F/M and lower the SRT.</li> <li>2. If sludge settles very quickly, leaving particles in suspension and effluent quality is decreasing, increase wasting as in 2.C.1 above.</li> <li>3. If present, and if effluent quality is decreasing, increase wasting as in 2. C. 1. above.</li> </ol> |

## Ashing, pinpoint floc, and straggler floc

---

| Observation   | Probable Cause  | Check  | Alternatives   |
|---|---|--|--|
| 3. Small light fluffy sludge particles rising to clarifier surface. Mixed liquor in settleability test settles slowly, leaving straggler in supernatant (straggler floc). | A. Overloaded aeration tank (high F/M) resulting in a young low density sludge. | <ol style="list-style-type: none"><li>1. Check and monitor trends for:<ol style="list-style-type: none"><li>a. Decreasing MLVSS, mg/L</li><li>b. Decreasing SRT.</li><li>c. Increasing F/M.</li><li>d. Decreasing aeration for the DO.</li></ol></li><li>2. Check wasting schedule.</li><li>3. Check to see if organic loading from sidestream flows contributes significantly to overall process loading.</li></ol> | <ol style="list-style-type: none"><li>1. Decrease wasting rates by not more than 10 to 15 percent per day.</li><li>2. If batch wasting, avoid wasting at the time of day when the BOD load is increasing.</li><li>3. Include BOD load from side stream in F/M calculations</li></ol> |

APPENDIX P

TROUBLESHOOTING ACTIVATED SLUDGE PROCESSES  
(Source: Ronald Schuyler, P.E.)

## Unit 4: Troubleshooting Activated Sludge Processes

---

Introduction Excess  
Foam  
High Effluent Suspended Solids  
High Effluent Soluble BOD or Ammonia Low  
effluent pH

---

### Introduction

Review of the literature shows that the activated sludge process has experienced operational problems since its inception. Although they did not experience settling problems with their activated sludge, Ardern and Lockett (Ardern and Lockett, 1914a) did note increased turbidity and reduced nitrification with reduced temperatures. By the early 1920s continuous-flow systems were having to deal with the scourge of activated sludge, bulking (Ardern and Lockett, 1914b, Martin 1927) and effluent suspended solids problems. Martin (1927) also describes effluent quality problems due to toxic and/or high-organic-strength industrial wastes. Oxygen demanding materials would bleedthrough the process. More recently, Jenkins, Richard and Daigger (1993) discussed severe foaming problems in activated sludge systems.

Experience shows that controlling the activated sludge process is still difficult for many plants in the United States. However, improved process control can be obtained by systematically looking at the problems and their potential causes. Once the cause is defined, control actions can be initiated to eliminate the problem.

Problems associated with the activated sludge process can usually be related to four conditions (Schuyler, 1995). Any of these can occur by themselves or with any of the other conditions. The first is foam. So much foam can accumulate that it becomes a safety problem by spilling out onto walkways. It becomes a regulatory problem as it spills from clarifier surfaces into the effluent.

The second, high effluent suspended solids, can be caused by many things. It is the most common problem found in activated sludge systems. Sometimes a suspended solids problem carries with it a particulate-matter BOD problem if the effluent TSS gets quite high. Ordinarily, one mg/L of effluent TSS produces about 0.5 mg/L BOD<sub>5</sub>. At low values of BOD<sub>5</sub> plus TSS, the sum of the soluble BOD<sub>5</sub> and BOD from TSS values often equals the TSS value.

The third is high concentrations of soluble materials traveling through the system and not being properly treated. BOD bleed-through is rare in domestic treatment systems where

problems are usually related to particulate BOD contained in suspended solids. However, excess ammonia can often appear in domestic effluents. BOD bleed-through is much more common in industrial systems or combined domestic/industrial systems where slowly metabolized compounds cannot be stabilized in a short detention-time activated sludge system.

The fourth general problem relates to low effluent pH. It is found most often in geographical areas with naturally low-alkalinity water supplies where extended aeration and/or nitrification processes are used. It is usually fairly easy to control. However, the problem can also be caused by low influent pH and control may be more difficult.

Schuyler (1995) has identified 32 different conditions for one of these four effluent problems to exist. These are shown in the following two-page troubleshooting guide. There are probably many other situations, but these represent the vast majority of the significant problems. The following discussion addresses each of those 32 conditions and the process control changes that should be made to eliminate the problem. While using this chart, it must be remembered that elimination of one problem may allow another problem to show up. Further, one condition may overshadow another such that the second condition cannot be observed until the first is eliminated. Finally, it is difficult to precisely define control actions relative to specific numbers, such as an MCRT of 5 days or a return rate of 25 percent of Q. Therefore, most control actions are discussed relative to the direction in which change is needed. For instance, for condition 23, the control action is to decrease wasting and return. The actual amount depends on actual conditions and cannot be specified here. A plastic laminated wall chart is available from Rothberg, Tamburini, & Winsor, Inc.

## Excess Foam

Conditions 1 through 5 relate to excess foam in the system (Jenkins, et al., 1993). When considering foam problems the question must be asked, "Is the amount of foam that exists a problem?" If it is not a problem, the situation may be better left unresolved. Many people observe foam and consider it a problem when it is not. For instance, a dark leathery *Nocardia* foam may look bad on an aeration tank but may not be affecting effluent quality. However, the situation may arise where someone's boss or the public thinks it's a problem; then it becomes the operator's problem.

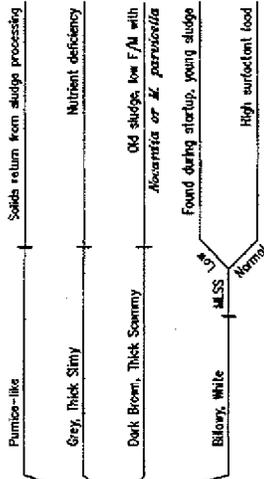
### Condition 1- Pumice-Like Foam

This type of foam often appears gray but if one looks closely, they observe that the foam has a large number of dark specks. This foam is usually due to solids returned from sludge processing. It may be due to poor solids capture from a belt press or a centrifuge or from digester supernatant return that contains excess solids. The key to improvement of this condition is to improve the solids capture in the sludge processing scheme.



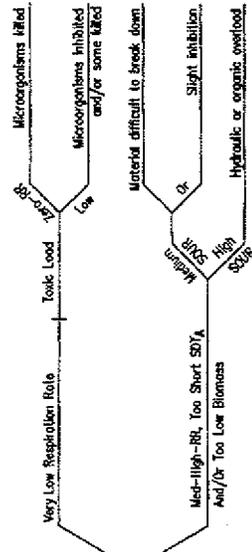
DO = Dissolved Oxygen  
 SRT = Solids Retention Time In The Aerator  
 MLRT = Mean Cell Residence Time  
 SRT = Mean Cell Residence Time  
 SRT = Specific Oxygen Uptake Rate  
 Oxidative Phosphorylation To Oxidize The Sludge  
 Treatment Pressure Tanks To Underdrains The  
 Sludge Microorganisms Grow Faster

**Excess Foam**



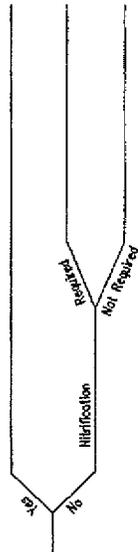
| CONDITION | REQUIRED PRESSURE | OBJECTIVE              | NORMAL CONTROL ACTIONS   |
|-----------|-------------------|------------------------|--|
| ①         | Misc.             | Reduce solids return   | Improve solids capture in sludge processing.   |
| ②         | Misc.             | Add nutrients          | Add $\text{NH}_3$ or $\text{NO}_2^-$ if $\text{NH}_3 + \text{NO}_2^- + \text{NO}_3^- > 1 \text{ mg/L}$<br>Add $\text{H}_2\text{PO}_4$ if $\text{PO}_4^{3-} > 0.5 \text{ mg/L}$ |
| ③         | Treatment         | Decrease TSU           | Increase waste, remove foam from system.   |
| ④         | Oxidative         | Increase TSU           | Decrease waste.  |
| ⑤         | Oxidative         | Increase TSU and SRT A | Decrease waste and return.   |

**High Soluble  $\text{BOD}_5$  or  $\text{NH}_3$**



|   |           |   |   |
|---|-----------|---|---|
| ⑥ | Oxidative | Remove toxic material<br>Increase TSU, decrease F/M | Decrease wasting.   |
| ⑦ | Oxidative | Remove toxic material                               | Decrease wasting, decrease return.                        |
| ⑧ | Oxidative | Increase SRT, decrease F/M                          | Decrease wasting, decrease return.                        |
| ⑨ | Oxidative | Increase SRT, decrease F/M                          | Decrease wasting, decrease return.                        |
| ⑩ | Oxidative | Increase SRT, decrease F/M                          | Decrease wasting, decrease return.<br>Initiate stop feed. |

**Low Effluent pH**



|   |           |                    |   |
|---|-----------|--------------------|---|
| ⑪ | Misc.     | Increase pH        | Chemically adjust pH<br>Excess pretreatment coag.               |
| ⑫ | Oxidative | Denitrify          | Use on/off aeration or mixic selector.<br>Chemically adjust pH. |
| ⑬ | Oxidative | Stop nitrification | Decrease wasting, decrease TSU.<br>If not possible, see #31.    |

Figure 341 Activated Sludge Process Control Troubleshooting Chart

1600 STOUT STREET, SUITE 1600 DENVER, COLORADO 80202 FAX 303-625-0642  
 303-625-5999  
 Kohberg, Tamburini & Winsor, Inc.

## **Condition 2 - Slimy Foam**

A grayish slimy foam that is very thick is commonly caused by nutrient deficiencies. It is often noted with a slime bulking condition. Those deficiencies may be either nitrogen or phosphorus. The solution usually involves addition of the limiting nutrient, such as ammonia to provide nitrogen, or phosphoric acid to provide phosphorus. There is usually enough nutrient if the ammonia plus nitrate in filtered (0.45  $\mu\text{m}$ ) effluent is greater than 1 mg/L and the soluble orthophosphate is greater than 0.5 mg/L (Jenkins, et al., 1993). However, in certain cases where easily degradable, soluble BOD is available, higher N and P concentrations may be necessary.

## **Condition 3 - Dark Brown, Thick, Scummy Foam**

Old sludge conditions usually cause a dark brown, thick, scummy foam. It is usually caused by the growth of *Nocardia* or *Microthrix parvicella*, both of which grow at the high MCRT/low F/M condition associated with old sludge. A treatment pressure is required to decrease the total sludge units in the system. Thus, one must increase wasting and try to remove foam from the system. Once *Nocardia* has started to grow profusely, it is difficult to eliminate through increased wasting. Therefore, removal of foam from the system becomes more important. Foaming due to *M. parvicella* appears to occur more during colder temperature conditions while *Nocardia* can bloom profusely under higher temperature conditions. Both also appear to like oils and grease in their diets.

## **Conditions 4 and 5 - White Billowy Foam**

White billowy foam is caused by high concentrations of surfactants such as detergents. It is not nearly the problem today that it was before biodegradable detergents were used. Condition 4 occurs at start-up of a system where a young sludge exists due to low mixed liquor suspended solids concentrations. In this condition there are just not enough solids present to break the surface tension of the surfactant bubbles that form. Thus, billowy white foam can accumulate on the aeration tank and can even be blown around by the wind. The condition is usually short-lived since at start-up the operator is usually applying oxidative pressure by increasing the total sludge units in the system. If the condition occurs due to previous excessive wasting, the solution is still to decrease wasting and increase the total sludge units in the system.

Condition 5 is found when there are higher concentrations of suspended solids. The cause is usually a very high surfactant load such as may be found when certain industrial processes are cleaned. Although there is a higher suspended solids concentration, it is still not high enough to break the surface tension of the surfactant bubbles. Again, an oxidative pressure is required to increase the total sludge units by decreased wasting and it is also worthwhile to increase the solids detention time in the aerator by decreasing the return flow rate.

## High Effluent Suspended Solids

High effluent suspended solids are usually caused by one of two conditions: either individual particles that will not settle are discharged or the sludge blanket in the clarifier washes out. Either of these can cause conditions 6 through 24 to occur. Look first at clarifier blanket washout related to conditions 6 through 17. In this situation, the sludge blanket in the clarifier actually rises close enough to the surface so that it washes over the effluent weir. To learn the reason for the clarifier-blanket washout, the first thing to do is to look at the sludge settleability. If the problem is not a blanket wash-out, it is individual particle washout. The individual particles may be tiny pin-floc, large straggler-floc or individual, dispersed cells. Physical observation of the effluent and microscopic observation of the mixed liquor or effluent will show which type or combination of types of individual particles is involved.

### **Hydraulic Overload ~ Conditions 6 and 7**

If the settling test or diluted settling test shows that the sludge settles well, then the blanket washout is usually due to too many solids in the clarifier.

Condition 6 is caused by hydraulic overload of the clarifier. It results when too many solids are pushed into the clarifier and they are not physically returned fast enough to the aeration tank. There are just too many solids applied to the clarifier. The required pressure to eliminate the problem is oxidative. The objective is to decrease the solids load to the clarifier by initiating step feed or even going to contact stabilization. If step feed or contact stabilization are not available, a short-term decrease in solids load to the clarifier can be accomplished by turning the air off in the aeration tank for a short time. This allows the solids to settle in the aeration tank. This reduces the solids load on the aeration tank while at the same time allows the sludge return system to return solids from the clarifier to the aeration tank. The same approach can be used to manage short-duration daily peak flows or other short-term peaks such as storm inflows or things like weekends at ski areas. However, the on-off approach will not work if the aeration basin discharge is from the bottom of the tank.

Condition 7 occurs due to an overload of the return system, not a hydraulic overload. The actual solids loading to the clarifier is not excessive, but the solids are just not returned fast enough. A treatment pressure is usually required, decreasing the clarifier sludge units. However, the problem may be caused by something much simpler and can be handled by an increase in the return rate. If there is a physical problem such as a clogged return line, clean the line.

### **Problems with Poor Settling**

Before the reason for poor sludge settleability can be pinpointed, a diluted settleometer test must be run. A simple old-sludge condition, with just too much sludge in the system, will show greatly improved settling in the diluted test. However, a bulking situation, even though it shows some improved settling, will not show large improvement.

### **Condition 8 - Excessive Old Sludge**

As mentioned above, this is pinpointed through the diluted settleometer test, which shows a great improvement in sludge settling. The required pressure is a decrease in the total system sludge mass. Increased wasting is required to accomplish that objective. This problem is very common.

### **Conditions 9 through 17 ~ Bulking**

Bulking has been the scourge of activated sludge ever since flow-through systems began being used in the 1920s. It can be caused either by production of slime or growth of filamentous organisms.

#### **Condition 9 - Slime Bulking**

Slime bulking (Jenkins, et al., 1993) is usually caused by a nutrient deficiency. As in Condition 2, ammonia or nitrate must be added if the ammonia plus nitrite plus nitrate is less than 1 mg/L. Phosphate must be added if the phosphate is less than 0.5 mg/L in the effluent. Slime bulking is usually associated with industrial waste, but may be found in municipal systems that have high concentrations of industrial wastes discharged to them. Even higher concentrations of N & P may be required with certain industrial wastes. This is true if the organic loading comes from easily metabolized materials, such as simple sugars, short-chain organic acids, or alcohols. These may be metabolized so rapidly that excess N and P are required in the system to ensure that the local concentrations are high enough. Complete mixing may also help in this situation.

#### **Condition 10 - Foam Trapping**

Systems can trap foam as in Condition 3 where *Nocardia* and *Microthrix parvicella* float to the surface. The key to removing the problem is to remove the foam from the system. Increased wasting will help some, but this will often have negligible benefit. A short-term solution includes some facilities using a vacuum truck to remove the foam from the surface. A long term solution includes eliminating grease from the influent.

#### **Condition 11 - Low DO Bulking**

Type 1701, *Sphaerotilus natans*, and *Haliscomenobacter hydroxsis* have all been known to grow profusely under low dissolved oxygen conditions. In recent years, it came to light that *Microthrix parvicella* also grew well under low DO conditions at high MCRT. Also, it was not known until recently that as the food-to-microorganism ratio increases, aeration basin dissolved oxygen also needs to increase, otherwise low DO bulking can occur. For instance, to protect a system with an F/M of approximately 1.0, almost 5 mg/L DO is required (watch potential denitrification problems). That F/M is defined as pounds of COD removed per pound of ML VSS in the aeration tank (Jenkins, et al., 1993).

Objective number one is to increase the DO, but in certain cases that is impossible. Objective number two would be to increase the MCRT, which in turn would decrease the F/M ratio. An MCRT increase would be accomplished with a decrease in wasting. Finally, a third objective

would be to develop a selector section that could operate anaerobically, anoxic ally, or aerobically. Jenkins, *et al.* (1993), indicate that any of the three types of selectors will work on low DO filaments.

### **Condition 12 - Low pH**

Growth of fungi is common in the fruit processing industry where a low pH exists along with a high sugar concentration. To get rid of low pH bulking, the objective is to increase the pH by adding either a caustic solution or a buffer solution to increase the alkalinity. A possibly better alternative is to provide pretreatment to eliminate the low pH initially. A third process control change would involve decreasing any nitrification that is occurring, since nitrification tends to depress aeration tank pH. Or as a related solution, increase denitrification in the aeration tank to increase alkalinity and pH.

### **Condition 13 - Nutrient Deficiency Bulking**

Types 021N, 0041, 0675, and *Thiothrix* have been known to cause bulking when deficient in either nitrogen or phosphorus (Jenkins, et al., 1993). The control objective is to increase nutrients so the ammonia plus nitrite plus nitrate is greater than 1 mg/L in the effluent, and phosphate is greater than 0.5 mg/L in the effluent.

### **Condition 14 - Sulfide Bulking**

*Thiothrix*, *Beggiatoa*, and types 021N and 0914 oxidize sulfide into elemental sulfur, depositing sulfur granules within the cell (Jenkins, et al., 1993). The control objective is to remove the source of the sulfide. Preaeration oxidizes the sulfide so it is not available to the filaments. Better aeration and mixing help if the sulfide is being formed in the treatment process itself. There is also the possibility that addition of iron compounds such as ferric chloride or ferrous sulfate would chemically bind the sulfide, making it unavailable for the microorganisms.

### **Condition 15 - Readily Metabolized Substrate Bulking**

Types 1851, 021N, *Nostocoida limicola*, *H. hydroxsis*, *S. natans*, and *Thiothrix* species all can rapidly metabolize short-chain organic acids (Jenkins, et al., 1993). Industrial systems may receive organic acids directly in the influent and biological nutrient removal (BNR) systems may produce those acids, as do anaerobic selectors. The control objective is to remove the organic acid source either through pretreatment or installation of an appropriate selector (aerated, anoxic, or anaerobic).

### **Condition 16 - Slowly Metabolized Substrate**

Types 0041, 0675, and 0092 along with *M. parvicellaare* known to grow well on slowly metabolized food. There are no real answers to controlling this growth to date, but it appears that maintaining good mixing and proper dissolved oxygen throughout the aeration process helps. These are also associated with older sludges. Therefore, reducing MCRT often reduces their growth.

## **Condition 17 - Surface Seeding**

Organisms such as *Sphaerotilus natans*, *Thiothrix*, *Beggiatoa*, fungi, and type 1701 can grow on upstream surfaces such as pipes or attached growth pretreatment systems. As these organisms slough off, they provide a large population of filaments for the aeration tank. If the environment in the aeration tank is not conducive to growth of these filaments, they will die out without proliferating. However, if they find a suitable environment in the aeration tank, they will proliferate accordingly. Therefore, the answer to control is to make sure that the aeration system provides enough DO, removes sulfide, or does whatever else is necessary to remove good filament growth conditions in the aeration tank.

## **Conditions 18, 19, and 20 - Pin-floc**

Pin-floc is tiny, usually dark, pinpoint-sized floc associated with very old sludge. Three different problems, specifically numbers 18, 19, and 20, are associated with pin-floc.

Condition 18. Pin-floc is often found in situations where the treatment plant is grossly underloaded and the mixed liquor suspended solids cannot be reduced any further than the present value. If it is reduced, the concentration gets so low that effective settling is impossible. Normally, one would try to reduce the MCRT, but this requires wasting and a reduced MLSS and it seldom works in this case. It may be worth trying to grow some filaments, such as low DO filaments, that would slow the settling and improve the capture of solids. Maintaining a DO between 0.1 and 0.5 in the aeration tank will usually allow low DO filaments to grow. Be careful!

Condition 19. Pin-floc is also associated with denitrification in the clarifier. Bacteria convert the nitrate to nitrogen gas and the resulting bubbles buoy floc particles to the surface. Ashing or clumping is often seen. A treatment pressure is required by reducing the total sludge units in the system. A slight increase in wasting usually eliminates the problem, however increased returns may also be required. If an increased return rate is used, be sure the other process demands, e.g., SDT A are met. Too-high return rates are very common. The use of on/off aeration or an anoxic zone in the aeration tank may also be helpful. It allows the denitrification to occur in the aeration tank where it is not a problem rather than in the clarifier where it is a problem.

Condition 20. Pin-floc also occurs in systems where solids are unintentionally being returned from solids processing. Excessive solids in anaerobic or aerobic digester supernatant or improper solids capture from sludge dewatering systems can all cause excessive loads of tiny sludge particles that will show up as pin-floc. They may or may not be associated with denitrification, so one has to be careful to decide which is causing the problem.

## **Conditions 21 and 22 - Straggler Floc**

Straggler floc is large, light colored, very fluffy floc that may or may not be filamentous. Microscopic observation will quickly show if it is filamentous or nonfilamentous. The effects of straggler floc are made worse by poor clarifier design and by high influent or return flows. Reducing return rates often helps.

Condition 21. All of the filamentous growth conditions, Conditions 11 through 17, can cause filamentous straggler floc development and the control actions associated with those should be followed. With severe cases during peak flows, try on/off aeration or step-feed. If that does not work, clarifier modification may be required.

Condition 22. Nonfilamentous straggler floc may be observed where changes in organic loading have caused certain flocs to grow very quickly. An oxidative pressure is needed, which increases the total sludge units and decreases the food-to-microorganism ratio. Thus, a slight decrease in wasting and a slight decrease in returns often solves the problem.

## **Conditions 23 and 24 - Dispersed Growth**

Dispersed growth is growth of individual bacterial cells or very tiny floc. The specific oxygen uptake rate (SOUR) will help identify the cause for the dispersed growth.

Condition 23. Very fast growth conditions, such as those seen at start-up can exhibit dispersed growth. It is shown by extremely high SOURs. An oxidative pressure is required that increases the total sludge units and decreases the F/M ratio. Again, as in

Condition 22, a decrease in wasting and a decrease in return will usually help the condition.

Condition 24. A toxic load can also cause dispersed growth. This case is shown by a very low OUR or SOUR. Once the toxic load has passed, an oxidative pressure is needed to increase the total sludge units and decrease the food-to-microorganism ratio. Thus, a decrease in wasting and decrease in return is appropriate. Remember, excessive recirculation of return sludge for bulking control can cause dispersion of cells.

## **High Effluent Soluble BOD or Ammonia**

Conditions 25 through 29 all relate to high soluble BOD or ammonia in the effluent. It is important to determine the respiration rate because the specific cause of the problem can easily be determined with the respiration rate, or SOUR.

### **Conditions 25 and 26, very low SOUR**

Condition 25 is shown by a zero SOUR and is caused by the fact that all of the microorganisms have been killed. They cannot use the oxygen. Once the toxic material is removed, it is imperative that the total sludge units are increased and the food-to-microorganism ratio is decreased, thus a decrease in wasting is required. If the SOUR is low, then Condition 26 is shown. The microorganisms were either inhibited, or a certain number, but not all, of the microorganisms were killed. In either case, an oxidative pressure is needed again once the toxic material is removed. A decrease in wasting and a decrease in return is effective until the mass of live microorganisms has been increased to the level needed for proper treatment.

### **Conditions 27 through 29, medium to high SOUR**

If the respiration rate or SOUR is medium to high, then a non-toxic situation exists. Condition 27. A medium SOUR can be due to the material in the influent being extremely hard for the microorganisms to break down. If this is the case, an oxidative pressure is needed and an increase in the solids detention time in the aerator and decrease in F/M is required. Thus, decreased wasting and decreased return will help. This supplies more microorganisms and more SDT A for the microorganisms to do the job.

Condition 28. A medium SOUR can also be found with slight inhibition, a condition very similar to Condition 26 and decreased wasting and decreased return should help.

Condition 29. A high SOUR or high effluent  $\text{NH}_3$  relates to a hydraulic or organic overload. In this case, there are not enough microorganisms or enough time in the aeration tank. to adequately treat the BOD or remove the ammonia. In this case, an oxidative pressure is needed to increase the solids detention time in the aerator and to decrease the food-to-microorganism ratio. Decreased wasting and decreased return will help.

Step Feeding or contact stabilization can also be very effective with condition 29. This reduces the solids loading on the clarifier, while allowing maintenance of a larger mass of microorganisms.

## Low Effluent pH

The last general condition that requires consideration is low effluent pH, conditions 30-32. It is usually caused by one of two reasons, low influent pH or *low* alkalinity water with nitrification. Either can cause regulatory noncompliance.

Condition 30. If the influent pH is low (acidic), there is a good chance that the condition will go through the plant and show-up in the effluent. Chemical addition to raise the pH is the immediate solution. Lime, soda ash, or sodium bicarbonate are normally used for pH adjustment. However, the ultimate solution is to eliminate the low pH source from the collection system by enforcing pretreatment requirements. An industrial system may have to live with pH adjustment.

Condition 31. If the influent pH is satisfactory, then the low effluent pH is usually caused by nitrification in combination with low natural alkalinity in the wastewater. If ammonia removal is required, then nitrification must continue. Use of on/off aeration or provision for an anoxic zone often returns enough alkalinity to satisfactorily raise the pH. However, if neither of these is possible, then pH adjustment similar to Condition 30 may be required.

Condition 32. With satisfactory influent pH near 7.0 and nitrification not required, the MCRT or DO can often be reduced enough to inhibit nitrification. With no nitrification, there is no alkalinity reduction through the aeration process and the pH remains stable. However, in systems that naturally nitrify, such as extended aeration, a solution for Condition 31 may have to be applied, if MCRT and DO control cannot provide a solution.

### References

Ardem, E. and W. T. Lockett. 1914a. Experiments on the oxidation of sewage without the aid of filters. *J. Soc. 01 Chemical Industry (England)*, 33:523-539.

Ardem, E. and W. T. Lockett. 1914b. The oxidation of sewage without the aid of filters. Part II. *J. Soc. of Chern Industry (England)*, 33: 1122-1124.

Martin, A. J. 1927. *The Activated Sludge Process*. MacDonald and Evans, London.

Jenkins, D., M. G. Richard and G. T. Daigger. 1993. *Manual on the Causes and Control of Activated Sludge Bulking and Foaming*. Lewis Publishers, Inc., Chelsea, MI.

Schuyler, R.G. 1995. *Activated Sludge Process Control Troubleshooting Chart*.

Rothberg, Tamburini and Winsor, Inc., 1600 Stout Street, Suite 1800, Denver, CO 80202-3126.

## APPENDIX Q

Calculations of Target MCRT for Nitrification  
(Source: Sterns & Wheeler for New York Department of Conservation)

## Calculation of Target Mean Cell Residence Time for Nitrification

### Required Input Data

- (1) Average Temperature in Aeration Tank, T \_\_\_\_\_ °C
- (2) Average Effluent Ammonia Concentration \_\_\_\_\_ mg/L (as N)
- (3) Average Aeration Tank Dissolved Oxygen Concentration \_\_\_\_\_ mg/L

### Determine Maximum Specific Growth Rate Corrected For Temperature ( $\mu_{\max,T}$ )

(4)  $\mu_{\max,T} = (0.65) * (1.055)^{(T - 25)}$

(5)  $\mu_{\max, \_} = (0.65) * (1.055)^{(\_ - 25)} = \_ \text{ day}^{-1}$

Enter temperature in °C from line (1)

### Determine Decay Rate Corrected For Temperature ( $k_d$ )

(6)  $k_d = (0.05) * (1.055)^{(T - 25)}$

(7)  $k_d = (0.05) * (1.055)^{(\_ - 25)} = \_ \text{ day}^{-1}$

Enter temperature in °C from line (1)

**Determine Growth Rate Correction Factor For Ammonia Concentration**

(8)  $CF_{NH_4^+} = \frac{NH_4^+-N}{K_N + NH_4^+-N}$

(9)  $K_N = (1.0) * (1.055)^{(T - 25)}$

(10)  $K_N = (1.0) * (1.055)^{(\text{---} - 25)} = \text{---} \text{ mg/L}$

Enter temperature in °C from line (1)

(11)  $CF_{NH_4^+} = \frac{\text{---}}{\text{---} + \text{---}} = \text{---}$

Enter  $K_N$  from line (10)

Enter effluent ammonia from line (2)

**Determine Growth Rate Correction Factor For Dissolved Oxygen Concentration**

(12)  $CF_{DO} = \frac{DO}{1 + DO}$

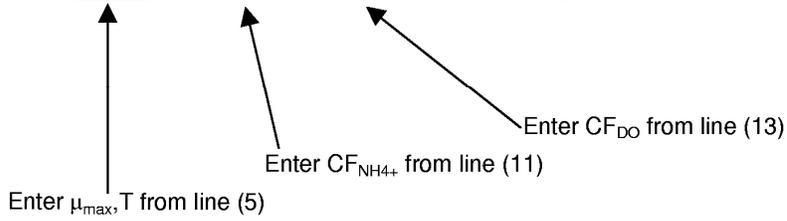
(13)  $CF_{DO} = \frac{\text{---}}{1 + \text{---}} = \text{---}$

Enter DO from line (3)

### Determine Growth Rate Corrected For Temperature, Ammonia and DO

$$(14) \mu_T = \mu_{\max, T} * (CF_{NH_4}) * (CF_{DO})$$

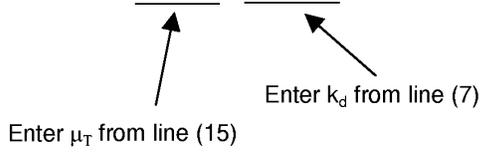
$$(15) \mu_T = ( \quad ) * ( \quad ) * ( \quad ) = \quad \text{day}^{-1}$$



### Determine Required MCRT

$$(16) MCRT = \frac{1}{\mu_T - k_d}$$

$$(17) MCRT = \frac{1}{\quad - \quad} = \quad \text{days}$$



APPENDIX R  
PROCESS CONTROL CALCULATIONS

## PROCESS CONTROL CALCULATIONS

### Return Activated Sludge (RAS) Rate

Method A - Settleability

$$Q_r = \frac{Q_{\text{MGD}} \times \text{MLSS}_{\text{mg/L}}}{\frac{1,000,000}{\text{SVI}} - \text{MLSS}_{\text{mg/L}}}$$

Where:

$Q_r$  = RAS (return activated sludge) Flow Rate in MGD

$Q$  = Flow through the plant in MGD

MLSS = Mixed Liquor Suspended Solids in mg/L

SVI = Sludge Volume Index

$$Q_r = \frac{\frac{\text{MLSS}_{\text{mg/L}}}{\text{RAS}_{\text{mg/L}}}}{1 - \frac{\text{MLSS}_{\text{mg/L}}}{\text{RAS}_{\text{mg/L}}}}$$

Method B – Secondary Clarifier Mass Balance

Where:

$Q_r$  = RAS (return activated sludge) Flow Rate in MGD

$Q$  = Flow through the plant in MGD

MLSS = Mixed Liquor Suspended Solids in mg/L

RASSS = Return Activated Sludge Suspended Solids in mg/L

$$Q_r = \frac{Q_{\text{MGD}} \times \text{MLSS}_{\text{mg/L}}}{\text{RAS}_{\text{mg/L}} - \text{MLSS}_{\text{mg/L}}}$$

Method C – Aeration Tank Mass Balance

Where:

$Q_r$  = RAS (return activated sludge) Flow Rate in MGD

$Q$  = Flow through the plant in MGD

MLSS = Mixed Liquor Suspended Solids in mg/L

RASSS = Return Activated Sludge Suspended Solids in mg/L

1. The basic control strategy is: 1) maintain an optimal distribution of solids between the aeration tank and the clarifier (solids belong in the aeration tank); 2) return the solids to the aeration tank quickly (avoid anaerobic conditions); and, 3) optimize the sludge concentration (thickly).
2. Return sludge flow rate changes should be made whenever: 1) the average daily flow changes; or, 2) the sludge settling characteristics change.
3. Return sludge flow rate changes should be limited to  $\pm 15\%$  -  $25\%$  per day
4. System response to RAS flow changes is somewhat rapid. Normally, the system responds within  $\frac{1}{2}$  the aeration detention time.

## Waste Activated Sludge (WAS) Rate

Constant MLSS

$$Q_W = (\text{Actual MLSS} - \text{Target MLSS}) \times (V_A) \times (8.34)$$

Where:

$Q_W$  = Waste sludge flow in pounds  
MLSS = Mixed Liquor Suspended Solids in mg/L  
 $V_A$  = Aeration tank volume

Constant F:M Ratio

$$Q_W \text{ in MLVSS} = \text{Actual MLSS} - \frac{\text{BOD}_{\text{inf}}}{\text{Target F:M}}$$

Where:

$Q_W$  = Waste sludge flow in pounds  
MLVSS = Mixed Liquor Volatile Suspended Solids in mg/L  
F:M = Food to Microorganism Ratio =  $\frac{\text{Influent BOD in pounds}}{\text{MLVSS in pounds}}$

$$Q_W = \frac{(\text{MLSS} \times V_A \times 8.34)}{\text{Target SRT}} - \text{ESS} \times Q \times 8.34$$

Constant Sludge Retention Time (SRT)

Where:

$Q_W$  = Waste sludge flow in pounds  
MLSS = Mixed Liquor Suspended Solids in mg/L  
 $V_A$  = Aeration tank volume  
ESS = Effluent Suspended Solids

1. Waste sludge control has two goals: 1) to remove the excess accumulation of sludge in the system; and, 2) to maintain the good sludge quality.
2. System response to waste activated sludge changes are normally slow; usually from 1 to 2 SRTs.
3. Waste sludge changes should be limited to  $\pm 15\%$  per day.

## APPENDIX S

### Wet Weather Operating Plan Guidelines

A wet weather operating plan is intended to provide operators with a guide to minimize the discharge of pollutants during wet weather and to protect their facilities from upset.

A. Key Elements. Every wet weather operating plan should contain the following key elements:

- Goals of the Plan. The goals section will define the overall objectives of the wet weather operating plan with respect to protecting water quality and plant performance.
  - Critical Components. The plan should list the critical components of the collection and treatment system that significantly impact wet weather performance. For each critical component, specific objectives should be defined.
  - Operating Guidelines. For each critical component, the plan will contain step by step guidance for operation, maintenance, and management procedures to be followed before, during and after a wet weather event.
  - List of Contacts. The plan should contain a list of important contacts that may be of assistance during wet weather events.
1. Goals of the Plan. The goals of the plan should define the water quality objectives of the collection and treatment system. For most systems with combined sewer overflows, operating decisions made during wet weather events can affect how much flow is treated at the wastewater treatment plant and how much flow is bypassed through CSOs. Difficult decisions must be made rapidly. These decisions may affect water quality in the receiving water at the CSOs, water quality in the receiving water at the plant, and performance of the plant during and after the wet weather event. Well defined goals for receiving water quality will help guide the development of operating guidelines for the plant and help guide decision making during wet weather events. It may be necessary to obtain advice from the Maine DEP in setting water quality priorities.
  2. Critical Components. The critical components are processes in the collection system (such as CSO regulators or pumping stations) or the treatment plant (such as bar screens or aeration tanks) which can significantly affect treatment of wet weather flow (or can be significantly affected by wet weather flow). The list of critical components is unique to each facility. One plant's critical components may not be critical at another facility. The Wet Weather Operating Plan is not intended as a substitute for the plant's operation and maintenance manual. Components that have no bearing on wet weather operations will not be listed. As an example, a collection system may include multiple wastewater pumping stations, but not all stations may be listed as critical components. Unlisted stations might serve a new portion of the sewer system that has no combined sewers and little I/I. Though regular operation and maintenance procedures are essential at an pumping stations, no special procedures may be needed at these stations during wet weather.

Any major unit process in the collection system or the wastewater treatment plant that is handling wet weather flows should be included on the list of critical components. Even if the process does not normally present special problems during wet weather it should be included on the list if it is handling wet weather flows. In addition, auxiliary processes that are impacted by wet weather flows should be included. If, for example, special provisions for sludge handling must be made during wet weather, a sludge thickening, stabilization or dewatering processes might be included on the list of critical components.
  3. Operating Guidelines. Operating Guidelines should be developed for each critical component identified in the collection system and treatment plant. For each component, tasks should be listed for completion before, during and after a wet weather event. Task descriptions should be brief and specific. The wet weather operating plan is intended to serve as a quick reference during a wet weather event. This is not the place for a detailed description of the theory behind a treatment process. The description must be specific enough, however, to describe exactly what needs to be accomplished. For example, "Check water level in influent channel" may not be specific enough. But, "Check water level in influent channel. Open feed gate to second bar screen if water level is above 3-foot mark on staff gauge" provides specific direction based upon a required observation.
  4. List of Contacts. Develop a list of contacts who can provide advice or assistance during a wet weather event. The list should include supervisors, and other involved public officials, equipment representatives and service organizations, local and state regulatory agencies, utilities, and emergency contacts such as fire department, police department and ambulance.
  5. Plan Development. The operation and maintenance staff who actually run the facility should develop the wet weather operating plan. If outside assistance is obtained for plan development, the plant staff should have a significant role in providing input, guidance, and review of the operating plan. The key steps in plan development are as follows:

- Identify personnel to be involved and form development team
- Break down plant and collection system into physical areas
- Break down areas into unit processes
- By unit process, list wet weather O&M procedures to be followed before, during, and after each wet weather event.
- Review and refine list of procedures
- Evaluate and continue to revise procedures (continuous process improvement)

At a large facility, the development team may include a large number of people with diverse roles at the plant. At a small plant, the development team may include the entire plant staff. Each of the steps in the development process can be initiated effectively through a brainstorming meeting with ideas contributed by all present. The detailed procedures can then be further developed in smaller work groups.

The completed Wet Weather Operating Plan should not be considered a final document. The plan should be subject to revision whenever operating experience at the plant demonstrate improved or additional procedures to be included. The plan should be kept in a three-ring notebook that can be easily modified as new revisions are developed. Even after the initial plan is developed, investigate some of the suggestions made in this manual, and other ideas that are developed at your plant. Test and compare various procedures to find new ways to treat more flow more efficiently at your facility. Never stop looking for new ways to make your plant provide better, more efficient performance and further reduce untreated overflows.

## APPENDIX T

### Sample Manual of Operations

**Albertville Municipal  
Wastewater Treatment Plant**

**Manual of Operations**

**Albertville, Maine**

*prepared by the*

**Albertville Wastewater Treatment Plant  
and  
Maine DEP**

**September, 2010**

## TABLE OF CONTENTS

|  | <u>Page</u> |
|--|-------------|
| Introduction .....                         | 1           |
| Statistical Process Control .....          | 2           |
| Waste Activated Sludge Flow Rate .....     | 4           |
| MLSS                                       |             |
| MLVSS                                      |             |
| F:M  |             |
| SRT (Sludge Age)                           |             |
| Sludge Quality .....                       | 7           |
| Microscopic Examination                    |             |
| SVI  |             |
| Oxygen Uptake Rates                        |             |
| Aeration Basin and Clarifier Observations  |             |
| Recycle Sludge Flow Rates .....            | 10          |
| Secondary Clarifier Sludge Blankets Depths |             |
| Recycle Secondary Solids                   |             |
| Aeration and Dissolved Oxygen .....        | 12          |
| Recycle Solids Chlorination .....          | 13          |

## INTRODUCTION

Activated sludge is a biological wastewater treatment process that brings together wastewater and a mixture of microorganisms under *aerobic* conditions.

The objective of activated sludge is to:

- Convert non-settleable, biodegradable materials to settleable solids and to produce a clarified effluent low in total suspended solids (TSS) and biochemical oxygen demand (BOD).

This objective is fundamentally accomplished by:

- reducing the organic materials using a complex biological community in the presence of oxygen and converting them to new cell mass, carbon dioxide and energy; and,
- producing solids that flocculate and are capable of settling in the clarifier.

It is the wastewater treatment plant operator's responsibility to ***control the treatment process by maintaining proper operating conditions so that the process meets effluent objectives in a cost-effective manner.***

**In the activated sludge process, there are three basic controls:**

- **waste sludge mass;**
- **return sludge mass; and,**
- **dissolved oxygen.**

There are many factors used as a basis for control of these variables. One of the first is knowing how much sludge is in the system, where the sludge is, how long it has been there, and how fast it is moving from one place to another.

1. pounds = concentration × volume × conversion factor, or  
pounds = mg/L × million of gallons × 8.34 lb/gal
2. Total Sludge, lbs = Aerator Sludge, lbs + Clarifier Sludge, lbs
3. Mean Cell Residence Time = Total Sludge, lbs/Waste Sludge, lbs, where  
Waste Sludge = Effluent TSS, lbs + Waste Sludge, lbs
4. Solids detention time in the clarifier = (clarifier sludge, lbs/return sludge, lbs/d) × 24 hrs/day
5. Solids detention time in the aerator = (Aerator Sludge, lbs/(Q + RSF) × MLSS) × 24 hrs/day

The purpose of this manual is to provide additional guidance to the wastewater treatment plant staff in order for them to make proper adjustment of the operational controls. Proper adjustment of operational controls leads to maintaining the proper "growth pressures" (or control variables). These guidelines will need to be used with operator judgment and updated as the process changes and new experience is gained over time.

## STATISTICAL PROCESS CONTROL

Statistical Process Control is the name given to a system of process control that uses statistical analysis of operating data to set control limits for certain operating parameters such as MLSS or MCRT. If the operator can maintain the parameters within the control limits, a good quality effluent can be produced. The basic statistical process control techniques should always be tempered and enhanced by good operator judgment. Statistical process control can be used to analyze the process so that appropriate actions may be taken to achieve and maintain a state of control and to improve the overall capability of the process. Control charts are the primary statistical process control tool used by operators.

A control chart is a graph showing plotted values of some control parameter and one or two control limits. It is used to determine if a process is in control, and to provide information to adjust operational controls.

A control limit, for the purpose of this guidance manual, is a line on a control chart used to establish the maximum or minimum range of a control variable.

Statistical control is the condition describing a process from which all special causes of variation have been eliminated. Special causes result in points on a control chart outside of the control limits.

The information illustrated by the control charts can be used by the staff to make operational control adjustments. The staff may make control adjustments of the operational controls to meet established control variable targets. The staff should consider trends and remember not to "over adjust" operational controls. The staff should attempt to always stay within the established control limits. There are four operational controls for this facility:

1. Wasting
2. Recycle Sludge Flow
3. Aeration Rate
4. Recycle Chlorination

# WASTE ACTIVATED SLUDGE FLOW RATE

## Background:

Sludge wasting is one of the most important operational controls. Sludge wasting controls the following:

1. Effluent quality
2. The F:M ratio, the Sludge Age (MCRT or SRT), and the mixed liquor concentration (MLSS).
3. The oxygen consumption
4. The nutrients required
5. Aeration basin foaming
6. Mixed liquor settleability

## Objectives for waste activated sludge flow rate control:

- Adjust the waste activated sludge flow rate to maintain a balance between the aeration basin solids and the incoming organic loading (BOD).
- Produce solids that flocculate and settle properly.

## Monitoring:

MLSS: Mixed Liquor Suspended Solids (MLSS) is the concentration of solids in the aeration basin as determined by standard total suspended solids laboratory analysis. The solids consist mostly of microorganisms; inert suspended matter and non-biodegradable suspended matter.

The target for aeration basin MLSS concentration is:

**Target: 2,800 mg/L (summer)**

**Target: 3,500 (winter)**

Upper Control Limit: 3,800 mg/L

Lower Control Limit: 2,400 mg/L

MLVSS: Mixed Liquor Volatile Suspended Solids (MLVSS) is the volatile or organic portion of the mixed liquor suspended solids, determined by the standard volatile suspended solids laboratory analysis.

The target for aeration basin MLVSS concentration is:

**Target: 2,300 mg/L (summer)**

**Target: 2,800 mg/L (winter)**

Upper Control Limit: 3,200 mg/L

Lower Control Limit: 2,000 mg/L

Solids Retention Time (SRT): A mathematical determination of the length of time activated sludge microorganisms spend in the aeration basin, expressed in days and calculated as:

$$\text{SRT} = \frac{(0.37 \text{ MG})(\text{MLSS, mg/L})(8.34 \text{ lb/gal})}{\text{WAS, lbs/day} + \text{EFF, lbs/day}}$$

where, WAS is the waste activated sludge in pounds per day (concentration, mg/L)(WAS flow rate, mgd)(8.34) EFF is the effluent TSS in pounds per day (TSS, mg/L)(Effluent flow rate, mgd)(8.34)

The target for the solids retention time is:  
**Target: 12 days (summer)**  
**Target: 14 days (winter)**  
 Upper Control Limit: 18 days  
 Lower Control Limit: 8 days

Food to Microorganism Ratio (F:M): A mathematical calculation of the mass of food, measured as BOD, divided by the mass of biological solids under aeration or MLVSS.

$$\text{F:M} = \frac{(\text{BOD, mg/L})(\text{FLOW, mgd})(8.34)}{(0.37 \text{ MG})(\text{MLVSS, mg/L})(8.34)}$$

where, BOD is the primary effluent BOD concentration and MLVSS is the aeration tank mixed liquor volatile suspended solids concentration

The target for the F:M ratio is:  
**Target: 0.14 (winter)**  
**Target: 0.12 (summer)**  
 Upper Control Limit: 0.17  
 Lower Control Limit: 0.09

**Operational Relationship**

| WAS Rate Change | F:M Ratio | MLSS      | SRT       |
|-----------------|-----------|-----------|-----------|
| Increase WAS    | Increases | Decreases | Decreases |
| Decrease WAS    | Decreases | Increases | Increases |

**The F:M Ratio compares the mass per day of food, measured as lbs. of BOD removed by the process with the pounds of microorganisms (measured as MLVSS) available to metabolize the food. The F:M Ratio increases as the SRT get shorter. The F:M Ratio decreases as the SRT gets longer.**

### **Control Procedure:**

Using information from the MLSS, MLVSS, SRT and F:M control charts, in combination with sludge quality information, the staff should adjust the wasting rate based on the targets and overall process status. Trends should be noted and knowledge of upcoming events should be used. The sludge wasting rate should not be changed more than ten to fifteen percent in one day. Wait one week or until observations and tests reveal a trend before making another change in the wasting rate.

1. Sample and analyze the mixed liquor to determine the MLSS concentration 3 times per week and the MLVSS concentration 1 time per week.
2. Calculate the SRT and F:M ratio.
3. Calculate the waste sludge required based on the following equation:

$$\frac{\text{Average pounds under aeration for the pervious week}}{\text{target SRT}} = \text{Waste sludge, pounds}$$

4. Evaluate the process based on sludge quality (microscopic, SVI, observations).
5. Determine the process status.
6. Plot the results of the MLSS, SRT, and F:M on control charts.
7. Evaluate the need to increase or decrease the waste activated sludge rate.
  - a. Are the control variables (MLSS, SRT, and F:M) above or below targets?
  - b. What is the process status based on sludge quality?
  - c. Is there a trend upwards or downwards in the primary effluent BOD?
  - d. Is there an anticipated increase or decrease in the primary effluent BOD?
  - e. Are the control variables (MLSS, SRT, and F:M) within the range defined by the upper and lower control limits?
8. Do not make extreme changes in the waste activated sludge rate.

**Note: Changes in waste rates will take 10 to 20 days to stabilize.**

## SLUDGE QUALITY

### Background:

The overall behavior of the biological solids is referred to as "sludge quality". Using the sludge quality method means that the operator studies the aeration basin, mixed liquor solids and secondary clarifiers for informative physical characteristics that help identify sludge quality and process status. The inferences of these physical findings are used to supplement the results of other process control variables, i.e., MLSS and F:M ratio, to make control variable adjustments.

### Objectives for sludge quality:

- Produce a mixed liquor that will form a strong floc and settles fairly rapidly as contrasted to a mixed liquor that settles very fast or very slow.
- Normally has a light brown color mixed liquor with a tan foam.
- Produce a mixed liquor that is active throughout the basin and stable at the end of the process as measured by the oxygen uptake rates.

### Monitoring:

#### Microscopic Examination:

The operator should examine a wet mount slide to observe indicator organisms and determine the abundance of filaments on a weekly basis.

#### Relative Number of Microorganisms vs. Sludge Quality

|  |
|--|
| <p>The target for filament observation is:<br/>Target: b some<br/>Upper Control Limit: c common<br/>Lower Control Limit: a few<br/>Reference: D. Jenkins, M. G. Richard, and G.T. Daigger, <i>Manual on the Causes and Control of Activated Sludge Bulking and Foaming</i>, 1986 (see Figure 13, page 35).</p> |
|--|

## Operational Relationship

| Suggested Causative Condition                             | Indicative Filament Types  |
|---|--|
| Low Dissolved Oxygen<br>(for the applied organic loading) | Type 1701, <i>S. natans</i> , <i>H. hydrossis</i> ,<br><i>M. parvicella</i>  |
| Low Organic Loading<br>(low F:M ratio)                    | <i>M. parvicella</i> , <i>Nocardia</i> spp., <i>H. hydrossis</i> ,<br>Types 021N, 0041, 0675, 0092, 0581,<br>0961, 1851 & 0803 |
| Septic Waste/Sulfides                                     | <i>Thiothrix</i> spp., <i>Beggiatoa</i> spp., Type 021N  |
| Nutrient Deficiency<br>(N and/or P)                       | <i>Thiothrix</i> spp., Types 021N, 0041 and 0675   |
| Low pH (<pH 6.5)  | Fungi  |

Reference: Jenkins et al., *Manual on the Causes and Control of Activated Sludge Bulking and Foaming*, 1986, page 73.

Sludge Volume Index (SVI): The volume in milliliters occupied by one gram of activated sludge after 30 minutes of settling.

$$SVI = \frac{(\text{Settled Sludge Volume after 30 minutes}) \times 1000 \text{ mg/g}}{MLSS, \text{ mg/L}}$$

The target for aeration basin solids SVI is:

**Target: 125**

Upper Control Limit: 150

Lower Control Limit: 100

Controlling settling behavior of sludge is a challenge. It requires a very good understanding of - and control over - the growth pressures that influence the continually changing biomass.

## Oxygen Uptake Rates:

The Oxygen Uptake Rate (OUR) test is a test procedure that determines the rate at which oxygen is removed from the mixed liquor by the activated sludge biomass. It is expressed as mg/L/hr oxygen uptake. The procedure is found in Standard Methods for the Examination of Water and Wastewater. The Specific Oxygen Uptake Rate or Respiration Rate relates OUR to biomass activity. This term gives the operator information related to the condition of the biomass. The unit expression is mg O<sub>2</sub>/hr/gram of volatile suspended solids. It indicates an activity level because the rate relates to oxygen removed by a given amount of microbial mass as measured by VSS.

The target for aeration basin effluent end OUR is:  
**Target: 9 mg/L O<sub>2</sub>/hr/gram MLVSS**  
Upper Control Limit: 12 mg/L O<sub>2</sub>/hr/gram MLVSS  
Lower Control Limit: 6 mg/L O<sub>2</sub>/hr/gram MLVSS

Activated sludge with an extremely high activity level (a young sludge) or extremely low activity level (old sludge) usually does not exhibit good flocculating characteristics. It is the flocculation that determines the way the sludge settles in the secondary clarifier.

## Aeration Basin and Clarifier Observations:

The operator should note the following aeration basin observations:

- Spray patterns
- Turbulence
- Color
- Foam

The operator should make the following secondary clarifier observations:

- Clarity
- Bulking
- Washout
- Clumping/Ashing
- Straggler Floc
- Pin Floc
- Secondary Clarifier Effluent Turbidity:

## RECYCLE SLUDGE FLOW RATE:

### Background:

Objectives for recycle sludge flow rate control:

- Adjust the recycle sludge flow rate to maintain a balance of solids between the secondary clarifiers and the aeration basin.
- Adjust the recycle sludge flow rate to obtain the maximum recycle solids concentration while preventing sludge septicity from developing.

### Monitoring:

Mass balance flow rate:

$$Q_r = \frac{(MLSS_{mg/L}) \times (Q_{MGD})}{RAS_{mg/L} - MLSS_{mg/L}}$$

where,

Q = Influent flow, mgd

Q<sub>r</sub> = Recycle flow, mgd

MLSS = Aeration basin mixed liquor suspended solids concentration, mg/L

Depth of Blanket (DOB): The distance from the clarifier water surface to the top of the sludge blanket. When subtracted from the total clarifier depth, this is equal to the blanket thickness (BLT).

The target for the blanket thickness is:

**Target: 1.5 feet**

Upper Control Limit 2.5 feet

Lower Control Limit 0.5 feet

Recycle secondary solids concentration:

The target for the recycle secondary solids concentration is:

**Target: 7,500 mg/L**

Upper Control Limit 10,000 mg/L

Lower Control Limit 5,000 mg/L

## Control Procedure:

The operator will use the information from the depth of blanket and recycle solids concentration in combination with judgment to establish the recycle rate.

**Recycle sludge flow can be thought of as a solids balancing process in which sludge is recycled from the clarifier to the aerator.**

### Operational relationship

|              | Depth of Blanket | Recycle Concentration |
|--------------|------------------|-----------------------|
| Increase RAS | Increases        | Decreases             |
| Decrease RAS | Decreases        | Increases             |

Too high or low recycle sludge flow rates can create problems with sludge quality and clarifier operation. High return rates increase the turbulence in the clarifier, decrease the aeration detention time for the biomass, and cause a billowing sludge blanket in the clarifier.

Too low return rates allow sludge to accumulate in the clarifier. This degrades sludge quality when anaerobic conditions in the sludge blanket occur.

In a properly balanced system, recycle sludge flow rate adjustments should not significantly change the F:M ratio. **F:M is controlled by wasting. Good sludge quality results from a proper sludge wasting strategy. Recycle redistributes sludge.**

The strategy of adjusting recycle flow rates does not work when there is a high blanket level in the clarifier caused by sludge bulking. In this case, the high blanket level would call for increasing the recycle sludge flow rate to lower the blanket. Increasing the recycle flow rate when the sludge is bulking will make the problem worse. A bulking sludge requires more settling time.

1. Determine the sludge blanket level for each clarifier.
2. Determine the recycle sludge concentration.
3. Calculate the minimum recycle rate based on the mass balance calculation.
4. Evaluate the need to increase or decrease the recycle rate for each clarifier.
  - a. Are the control variables (BLT and recycle concentration) above or below targets?
  - b. Is the recycle at least the minimum required by the mass balance calculation?
  - c. Is filamentous bulking a problem?
5. Based on the evaluation, increase or decrease the recycle flow rates by less than +/- 25 percent per day.

**Note: Changes in recycle rate will take 12 to 24 hours to stabilize.**

## **AERATION AND DISSOLVED OXYGEN:**

### **Background:**

Oxygen is required by the microorganisms to satisfy the oxygen demand exerted by BOD conversion and endogenous respiration. The contents of the aeration basin must also be sufficiently mixed to keep the mixed liquor solids in suspension and to uniformly mix the solids with the wastewater. In addition, oxygen must be dissolved in the liquid to maintain D.O. at the center of the floc and result in a residual D.O. concentration that doesn't promote excessive filamentous bacteria.

### **Objectives for oxygen addition are:**

- Provide oxygen in proportion to the organic (BOD) loading for proper biological metabolism.
  - If necessary, provide adequate oxygen for metabolism of nitrogen compounds
- Provide sufficient mixing.
- Optimize oxygen feed rates through D.O. aeration basin residual monitoring and management.

### **Monitoring:**

Dissolved oxygen: The amount of oxygen dissolved in the aeration basin liquid, expressed in mg/L.

The target for aeration basin dissolved oxygen (D.O.) residual is:

**Target: 1.0 mg/L**

Upper Control Limit 2.0 mg/L

Lower Control Limit 0.5 mg/L

Dissolved oxygen is monitored at the effluent end of each basin before it discharges over the weir.

### **Control Procedure:**

1. When the D.O. exceeds 3.5 mg/L, shut the aerators at the effluent end off.
2. The weirs are adjustable (with some difficulty) to either increase or decrease the aerator submergence.

## RECYCLE SOLIDS CHLORINATION

### Background:

Recycle solids chlorination is a short-term measure in response to filamentous bulking. Other short-term measures include:

- "sludge juggling"
- polymer addition to the secondary clarifiers

### Long-term measures to correct chronic filamentous bulking include:

- aeration basin pH control
- control of influent waste septicity
- nutrient addition
- changes in aeration rate
- changes in biomass concentration
- changes in waste feeding patterns

### Objectives for recycle sludge chlorination:

- Expose activated sludge to sufficient chlorine to damage filaments extending from the floc surface while leaving organisms within the floc largely untouched.

The chlorine dosage is adjusted such that its concentration is lethal at the floc surface but is sublethal within the floc.

### Monitoring:

SVI:

The target SVI to begin recycle solids chlorination is:

**SVI = 135 (5 day moving average)**

The target SVI to end recycle solids chlorination is:

**SVI = 135**

Microscopic examination:

The target for filament observation is:  
Target: 2 some  
Upper Control Limit: 3 common  
Lower Control Limit: 1 few  
Reference: D. Jenkins, M. G. Richard, and G.T. Daigger, *Manual on the Causes and Control of Activated Sludge Bulking and Foaming*.

Chlorine effects on filaments include, in order:

- a loss of intracellular sulfur granules
- cell deformity and cytoplasm shrinkage
- finally filament breakup and lysis

**Control Procedure:**

Chlorine dosage should be started low and increased until effective. Sludge settleability usually improves within 1-3 days if an adequate chlorine dosage is applied.

1. SVI: \_\_\_\_\_

2. Filamentous Bacteria Amount: \_\_\_\_\_  
(Enter: Few, Some, Common, Very Common, Abundant, or Excessive)

3. Enter chlorine dosage: \_\_\_\_\_ lbs Cl<sub>2</sub>/1,000 lbs MLVSS in aeration  
(Enter: Few or Some = 0, Common = 4; Very Common = 6; Abundant = 8; Excessive = 10)

4. Enter MLSS concentration: \_\_\_\_\_ mg/L

5. Enter the most recent MLVSS analysis: \_\_\_\_\_ % MLVSS

6. Calculate the pounds of MLVSS:

$$0.37 \text{ MG} \times 8.34 \times \text{_____} (\text{MLSS, mg/L}) \times \text{_____} \% \text{ MLVSS} = \text{_____}$$

7. Calculate chlorination rate:

$$\text{_____} \text{ lbs MLVSS} \times 1/1000 \times \text{_____} \text{ Cl}_2 \text{ Dosage} = \text{_____} \text{ lb Cl}_2 / 1000 \text{ lb MLVSS/day}$$

8. Round off result of #7 to nearest lb: \_\_\_\_\_ lb Cl<sub>2</sub>/day

9. Determine gallons of Sodium Hypochlorite required to deliver dosage calculated in #8.

$$\text{gallons NaOCl} = \frac{\text{pounds Cl}_2/\text{day}}{Z \text{ pounds available Cl}_2/\text{gal}} = \text{_____ gal /day}$$

where: Z = 0.44 for 5.25% NaOCl (common Chlorox bleach)

Z = 0.83 for 10.0% NaOCl

Z = 1.0 for 12.5% NaOCl

Z = 1.25 for 15.0% NaOCl

10. Set chlorination and record time of adjustment

11. Observe filaments and note SVI

12. Dosage should not exceed 10 lb Cl<sub>2</sub>/day per 1000 lb MLVSS.

## APPENDIX U

### Microbiology for Wastewater Treatment Plant Operators

Excerpted from a series of articles by Donald Albert, P.E.  
in the Maine DEP *O&M News*

## MICROBIOLOGY FOR WASTEWATER TREATMENT PLANT OPERATORS

Microorganisms including bacteria, protozoa and some multi-celled organisms do most of the work in a conventional secondary wastewater treatment plant. We commonly lump all the types of microbes together and call them "bugs". This series of articles will look at how the bugs grow and reproduce and at the factors which affect their growth and reproduction. Understanding how bugs work and what affects their growth and reproduction can help operators make their treatment plants run more efficiently and solve problems which may happen in the future.

All *aerobic* organisms (including humans) need three things for life: *water*, *air*, and *food*. To obtain energy for life, aerobic organotrophs (including human cells) require organic food and oxygen for controlled combustion of that food. These organisms (including human cells) must be bathed in water to function. Slightly more than 70 percent of the human body is water and approximately 80-percent of a microorganism is water.

Some organisms can live either with or without free oxygen. *Facultative* bacteria can, when free oxygen is not available, use oxygen from nitrate (NO<sub>3</sub>). Conditions where free oxygen is not available, but where oxygen is available from chemical compounds are called *anoxic* conditions. When free oxygen and combined oxygen in the form of nitrate is gone, *anaerobic* conditions exist. Sulfate compounds are used in anaerobic conditions. Some bacteria can live only in anaerobic conditions. Anaerobic sludge digesters use anaerobic bacteria to convert organic matter to methane gas. Most treatment plants use a combination of aerobic and mostly facultative bacteria in the treatment process.

Protozoa are also commonly found in wastewater treatment systems. Protozoa are microscopic animals that are strictly aerobic. Protozoa commonly eat bacteria and smaller protozoa. Different protozoa will thrive under different conditions. Some are more efficient at gathering food and will out-compete less efficient species. The relative proportions of protozoa types are highly dependent on the sludge age.

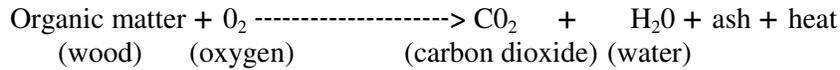
Human activities generate wastewater from households, business buildings and industrial facilities. As clean water is used by these activities, it accumulates various organic and inorganic chemicals and carries it away from the human populations. Aerobic decay of the organic matter in the water can result in localized oxygen depletion. Secondary biological wastewater treatment plants duplicate the natural use of organic matter by providing a good environment for the bugs to grow and reproduce under controlled conditions. The bugs remove the organic matter and thereby control the depletion of oxygen in the receiving waters. Biological wastewater treatment plants are artificial systems that are inserted into the natural cycles that sustain the food and air in our environment.

There are two characteristics of organic matter that are important to wastewater treatment plant operators. First, organic matter contains the element carbon which is an important part of the living cell. Second, organic matter burns (combustible) and releases energy during combustion. For example, if you place a piece of wood (organic matter) in a wood stove (reactor), open the damper (oxygen) and light the stove, it will burn and release energy as heat. More heat is released as you add more wood or open the damper. Heat is released as the chemical bonds that hold the various elements together are broken. These chemical bonds involve the sharing of electrons by the various elements (i.e., carbon, hydrogen, oxygen) in the compound.

When we speak of biological "burning" (or oxidation), it is not the change in heat energy, but the use of available energy stored in chemical compounds for growth and reproduction by the organisms that is important. Burning is a chemical oxidation and reduction reaction. Oxidation is defined as the addition of oxygen to a compound, the removal of hydrogen from a compound and the loss of an electron; reduction is the converse of oxidation. Oxidation and reduction must occur at the same time. The electron donor-

acceptor relationship characterizes the oxidation-reduction reaction.

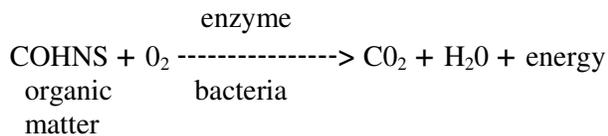
For example, as wood burns, the chemical reaction looks like this:



As the chemical bonds that hold wood together are broken, oxygen accepts electrons from the hydrogen in the wood and forms water. Carbon dioxide, ash or inert materials are left and heat is released. Without oxygen there is no electron acceptor and the reaction does not occur.

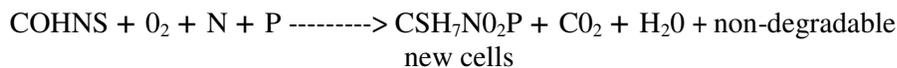
Aerobic organisms have four basic nutritional requirements: a carbon source, an energy source, and an electron donor and electron acceptor. Carbon is used to build new cells, energy is used for growth and reproduction, the electron donor and electron acceptor allows for the release of energy.

During biological oxidation of organic compounds by aerobic heterotrophic bacteria, organic matter is the source of energy and carbon, the electron acceptor is oxygen, the electron donor is hydrogen in the organic matter, and the by-products are water and carbon dioxide. As shown below, if oxygen is not available, the reaction does not occur.



Just as in the example of burning wood, as organic matter increases, more energy is released and more oxygen is required. In addition, a spark is needed to start the reaction. Bringing organic matter together with oxygen does not cause combustion. In the case of biological combustion, the "spark" comes from enzymes. Without them, the reaction cannot take place. Enzymes are specific water soluble proteins that are active within a small temperature range. This is why wastewater treatment bacteria must become acclimated to specific types of waste before they are able to break it down. Environmental conditions greatly influence the function of enzymes.

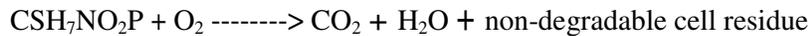
Now that we have discussed oxidation of organic matter as the way that bacteria obtain and store energy for growth and reproduction. Synthesis is the term used to describe the process in which new bacteria cells are generated. New bacteria cells are made up of carbon, hydrogen, nitrogen, oxygen, phosphorus, and other trace elements. As individual microorganisms grow and reach maximum cell size, the cell divides into two new cells. These two new cells grow and in turn divide. This type of reproduction is called binary fission. Under optimum conditions, bacterial cells may divide every 20 to 30 minutes. This rapid rate of reproduction is called logarithmic growth. When microorganisms find themselves in an abundance of food, reproduction occurs at logarithmic rate. The log growth phase continues until food is depleted. As more food is used up, the reproduction rate slows down. This period of decreasing rate of growth is called declining growth phase. The synthesis reaction is shown below:



As bacteria cells grow, they store energy and materials necessary to generate new cells. During synthesis organic matter (carbon), hydrogen, oxygen, nitrogen (ammonia), and phosphorus (ortho-phosphate) are needed to build new cells. In addition, sulfur, sodium, potassium, calcium, magnesium, iron, molybdenum, cobalt, manganese, zinc and copper are required in lesser amounts. Without these nutrients

new cells can not develop. The nutrient availability and balance also establish a competitive advantage for some microbial communities, particularly when nutrients are limited. Experience at wastewater treatment plants shows that nitrogen and phosphorus must be available at the same time and in proportion to the BODS loading. As a general rule, for each 100 mg/L of BOD, the microorganisms need 5 mg/L nitrogen and 1 mg/L phosphorus,

As long as adequate organic matter, air, and nutrients are available, bacteria will continue to grow and reproduce. Once the organic matter is depleted, endogenous respiration begins. During endogenous respiration, cells begin to use their own internal cell matter as the source of energy to sustain life.



We noted that when the source of food is depleted, the microorganisms stop growing at a logarithmic rate. Ideally, this is the growth where the bugs in a wastewater treatment plant should be. All the organic matter has been taken up by the bugs but they have not yet begun to die-off. The food (F) to microorganism (M) ratio (F:M) relates the amount of food available relative to the mass of microorganisms. The operator can use the F:M ratio to control the growth rate of the bugs in the system. Thus, F:M is an important factor which operators can use to control the biological treatment system.

In addition to organic matter, wastewater contains inorganic compounds such as ammonia. No Certain bacteria are capable of burning ammonia to release energy for growth and reproduction. These bacteria, called nitrifying bacteria, use ammonia-N as its source of energy and carbonate alkalinity as the carbon source. During nitrification the electron acceptor is oxygen, the electron donor is hydrogen in ammonia-N and the by-products are nitrite, nitrate, water and hydrogen ions.

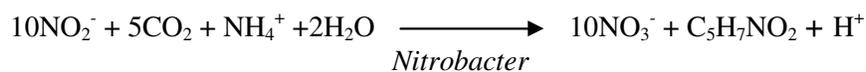
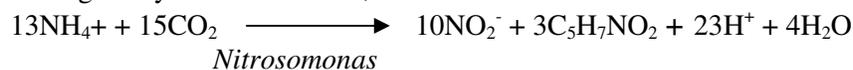
Nitrification is a two-step aerobic process. In the first step, ammonia is oxidized to nitrite by *Nitrosomonas*.



During the second step, nitrite is oxidized in nitrate by *Nitrobacter*.  $\text{NO}_2^- + 1/2\text{O}_2 \text{ ----} \rightarrow \text{NO}_3^-$   
The overall energy reaction is:



During the synthesis reactions,



When the energy and synthesis reactions are combined,



The total oxygen required is 4.57 pounds oxygen per pound of ammonia-N. By comparison, each pound of BOD removed requires about 1.3 pounds of oxygen. The total alkalinity required is 7.14 pounds alkalinity as CaCO<sub>3</sub> per pound of ammonia-N. Thus, full nitrification requires both oxygen and alkalinity to be readily available.

As discussed above, synthesis and nitrification. Biological denitrification involves the microbial reduction

of nitrate to nitrite, and ultimately nitrite to nitrogen gas. Unlike nitrification, a relatively broad group of bacteria can accomplish denitrification. Denitrifiers are found in most natural environments, including municipal wastewaters and sludges. Denitrifiers are facultative organisms: they can use either oxygen or nitrate as their terminal electron acceptor. In the process of denitrification, nitrate and nitrite act as electron acceptors in the respiratory electron transport chain in the same manner as oxygen. This transport chain is the fundamental mechanism by which cells generate energy. By using nitrate in place of oxygen the bacteria generate less energy. Similarly, more energy is generated using nitrate than sulfate. Control systems exist within bacteria that ensure the most efficient form of energy generation is utilized. Thus if oxygen is present, it will be used before nitrate, and if oxygen is not present, nitrate will be used before sulfate. Denitrifiers are able to switch from oxygen to nitrate. They do this by generating the enzymes required for denitrification. Between 2 and 3 hours is typically required for the bacteria to switch from an aerobic to an anoxic environment.

Control of denitrification occurs at the level of enzyme activity. Oxygen will inhibit the activity of the denitrifying enzymes. The oxygen concentration at which denitrification stops has been reported to be 0.2 mg/L in pure cultures. In activated sludge the reported values are 0.3 to 1.5 mg/L. Organic compounds serve as organic substrate (i.e., as carbon and electron donor) for denitrification. Bicarbonate alkalinity is produced during denitrification. The theoretical production is 3.57 mg alkalinity as  $\text{CaCO}_3$  produced per mg of nitrate reduced to nitrogen gas.

Thus far, we have been discussing the basic metabolic needs of the individual organisms. The term metabolic needs is used to define all the diverse reactions by which a cell processes food material to obtain energy and the compounds from which new cell components are made. We must now look at the diverse microbial population of the wastewater treatment system as a whole. Such systems rely on a population of many types of bugs to remove the organic and inorganic pollutants from the wastewater. As the nutritional and physical characteristics of the system change, conditions will favor certain types of bugs over others. These physical and nutritional conditions select the organisms best adapted to the environment. Further knowledge of the nutritional and physical factors affecting microbial growth is necessary to know what types of organisms may be expected to predominate in various environments. Kinetics is a term used to define the *rate* and amount of microbial growth. The kinetics of a system are related to the amount of food, oxygen and nutrients available to the system. Kinetics also depends on temperature, pH, mixing, MCRT, and hydraulic detention time in the aerator and clarifier. We have already discussed food, oxygen, and nutrients. Now we will talk about the physical parameters.

Temperature is one of the most important physical factors in the selection of species. Most organisms grow within a range of 30° - 40°C. The optimum is generally closer to the maximum than to the minimum. Growth at the minimum temperature is very slow and increases rapidly with increasing temperature, reaching a maximum at the optimum temperature and falling abruptly. For most microorganisms the growth rate increases two-fold for each 10°C rise in temperature. On the basis of their optimal growth temperatures, microorganisms are classified as psychrophile, mesophiles or thermophiles. Most microbial species are mesophilic, growing best between 20° and 45°C. Psychrophiles have optimum temperatures below 20° C, whereas thermophiles grow best above 45° C.

Another physical factor that, like temperature, influences the growth rate and limits growth is pH. In general, most bacteria have pH optima near neutral and minimum and maximum near 5 and 9. Most fungi prefer an acid environment and have minimum pH between 1 and 3 with an optimum pH near 5. Most protozoa are able to grow in the range 5 to 8, with an optimum pH near 7.

The degree and vigor of mixing can exert profound effects on the selection of species and the behavior of the species. Mixing tends to prevent localized differences in temperature, nutrients, dissolved oxygen, and pH. Mixing also impacts the solids separation process.

In an activated sludge plant, new biomass is produced as BOD is removed. This is called sludge yield. For every pound of BOD removed about 0.5- 1.0 pound of biomass is produced. Mixed liquor suspended solids (MLSS) results from the development of accumulation of biomass. "Building up" suggest that biomass can accumulate as it is produced. Biomass increases when the wasting rate is less than the growth rate. A drop in biomass occurs when sludge wasting exceeds the rate of new sludge growth .. As the number of microorganisms increases, the amount of food available to each organism decreases, and consequently, the rate of microbial reproduction decreases. Microbial reproduction varies with the availability, type and concentration of BOD.

Now that we have discussed biological denitrification and physical and nutritional conditions that encourage the growth of certain organisms. Sludge age significantly affects the "community composition" within the mixed liquor. For any species to survive, its growth rate must be greater than its washout rate. "Washout rate" implies that cells are lost from the inventory, and this occurs in at least three ways: 1) sludge wasting, 2) effluent TSS, and 3) death.

Many terms are used to describe the concept of sludge age. Mean Cell Residence Time (MCRT) is among the most popular. MCRT refers to how long the average cell remains in a secondary system before being removed. Secondary clarifier inventory is included, along with effluent suspended solids, in the MCRT calculation.

The hydraulic detention time is the amount of time the wastewater is retained in each individual unit reactors. Hydraulic detention times vary depending on the type of system. Suspended growth systems are normally categorized into three types: conventional activated sludge, with a detention time of 4-6 hours; extended aeration, with a detention time of about 24hours; and, contact stabilization, with an initial contact time of less about 30 minutes and a stabilization time of about 8 hours. Systems operating with detention times outside these detention times typically do not operate efficiently.

There are several different types of environmental shocks that will disrupt the operation of a wastewater treatment plant. A qualitative shock is a change in the nature of the energy (food) and carbon source in the influent. A quantitative shock also relates to the carbon and energy source, but involves a change in the concentration rather than the type of compounds. A hydraulic shock involves a change in the inflow rate to the treatment plant. A pH shock may have considerable effect on metabolism and on selection of species. A toxic shock is the introduction of toxic materials, organic or inorganic, into the influent.

Whether an organism will grow and the extent to which it will thrive is determined by the *law of the minimum*. According to this law the growth of an organism is limited by the amount of that one of its requirements which is present in minimum quantity relative to the overall requirements of the organism. The factor that controls growth in one situation may be food, or it may be phosphorus or nitrogen.

Natural selection of certain organisms and the establishment of competitive advantages are related to metabolic or kinetic factors. The type of food (organic or inorganic) will determine what types of microorganisms will thrive. The level of oxygen will determine whether aerobes or anaerobes will survive. The lack of a nutrient may allow certain filamentous bacteria to out complete other organisms for essential cell macro nutrients. The presence of sulfur may promote the growth of *thiothrix*, *beggiatoa*, and type 021 N. Fungus requires lower pH in order to function. The ratio of food to microorganism determines whether floc formers are generated or low F:M filaments such as *M parvicella*, *H. hydrosis*, *Nocardia*, types 021N, 0041,0675,0092,0581, 0961, and 0803 will dominate.

It is very important for wastewater treatment plant operators understand "growth pressures" so that metabolic and kinetic factors can be controlled to promote proper treatment. The most common variables that operators should understand and control include:

- BOD<sub>5</sub> and Nitrogen (type and amount of food)
- D.O. (dissolved oxygen)
- Mean Cell Residence Time (MCRT)
- F/M ratio (food to microorganism ratio)
- Temperature
- pH
- Nutrients (N & P)
- Toxins
- Hydraulics (detention time)
- Return Sludge Flow Rate

Many problems at waste treatment plants are related to a kinetic or metabolic factor(s). Grayish slimy foam is usually caused by nutrient deficiencies. *Nocardia* or *Microthrix parvicella*, grow at high MCRT. Most filamentous bulking problems are caused by a nutrient or DO deficiency, low pH, sulfide, or high MCRT. Pin floc is normally caused by high MCRT. Straggler floc is usually caused by low MCRT. A toxic load can cause dispersed growth.

One way to control unwanted bugs is to change the operation of the plant to bring about a "selector effect". A selector effect results from differences between floc forming and filamentous organisms. Floc-formers have a higher growth rate which provides a kinetic advantage at high substrate concentrations. Floc-formers have the ability to quickly take up and store substrate which can starve the filaments. Selectors can also make use of metabolic differences. Anoxic selectors make use of floc-formers ability to respire under anoxic conditions when dissolved oxygen is lacking but nitrate is present. Anaerobic selectors make use of floc-formers ability to attain energy through anaerobic fermentation or cleavage of high phosphate bonds.

Selector effects can be created by adding tanks to the process, by baffling or otherwise isolating a portion of one tank to achieve anoxic or anaerobic conditions or by operating in an on-off aeration, mode which promotes anoxic conditions during part of the treatment cycle. If you are considering the use of a selector to improve the treatment efficiency or to solve a filamentous bulking or other problem at your plant, you should first try to identify the root cause of the problem. Then you can decide if a selector will solve that problem or if another treatment pressure may give you better results.

I hope these articles encourage you to learn more about the microbiology of wastewater treatment.

## APPENDIX V

### Alkalinity as a Process Control Indicator

## ALKALINITY AS A PROCESS CONTROL INDICATOR

Alkalinity can be used to indicate the rate of biological activity in wastewater treatment plants. Aerobic reactions correspond to an alkalinity decrease, while anoxic and anaerobic reactions correspond to an alkalinity increase. Measuring and controlling alkalinity at certain points within the treatment plant can provide biological control.

### Alkalinity Defined

The alkalinity of water is a measure of its capacity to neutralize acids. It also refers to the buffering capacity, or capacity to resist a change in pH. Bicarbonates represent the major form of alkalinity in wastewater. Alkalinity is measured by titration and is reported in terms of equivalent calcium carbonate (CaCO<sub>3</sub>). It is common practice to express alkalinity measured to a certain pH. Phenolphthalein alkalinity is measured by titration to a pH of 8.3. Total alkalinity is measured by titration to a pH of 4.5.

### Biological Processes Reviewed

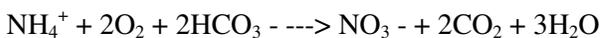
In wastewater treatment, the three forms of oxygen available to bacteria are dissolved oxygen (O<sub>2</sub>), nitrate ions (NO<sub>3</sub><sup>-</sup>), and sulfate ions (SO<sub>4</sub><sup>-</sup>). Aerobic metabolism uses dissolved oxygen, bacteria's most preferred oxygen source, to convert food to energy. A class of aerobic bacteria, nitrifiers, uses ammonia (NH<sub>3</sub>) for food instead of carbon-based organic compounds. This type of aerobic metabolism that uses dissolved oxygen to convert ammonia to nitrate is referred to as nitrification. Nitrifiers are the dominant bacteria after most of the organic food supply has been consumed. When dissolved oxygen is depleted, the next most efficient source of oxygen is nitrate. Denitrification, or anoxic metabolism, occurs when bacteria use nitrate as the oxygen source. Under anoxic conditions, the nitrate ion is converted to nitrogen gas while the bacteria convert food to energy. Anaerobic metabolism occurs when dissolved oxygen and nitrate are no longer present and bacteria must obtain oxygen from sulfate. In this process the sulfate is converted to hydrogen sulfide and other sulfur compounds.

### Alkalinity in Biological Reactions

Alkalinity can be used as an indicator of biological activity. Depending on conditions, each of the biological reactions will occur and change alkalinity at a certain and predictable rate. Measuring this rate of change will indicate the rate of biological reactions and allow for their control. Each type of metabolism - aerobic, anoxic and anaerobic - has a direct relationship to the bicarbonate concentration. Thus, when bacteria consume or produce compounds such as nitrate or ammonia there is a corresponding change in bicarbonate concentration.

Aerobic metabolism, in general, and nitrification, in particular, will *decrease* alkalinity by the following reaction:

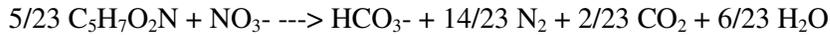
#### Nitrification (Aerobic)



Note that two bicarbonates are consumed for every ammonia that is converted to nitrate. For every part per million (ppm) of converted ammonia, alkalinity decreases by 7.14 ppm.

Anoxic metabolism, where nitrate is converted to nitrogen-gas, *increases* alkalinity by the following reaction:

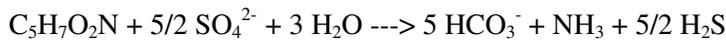
Denitrification (Anoxic)



Here, one bicarbonate is produced for every nitrate converted to nitrogen-gas. Alkalinity increases by 3.57 ppm for every ppm of nitrate converted.

Anaerobic metabolism also increases alkalinity as shown by the following reaction:

Sulfate Reduction (Anaerobic)



Alkalinity increases 17.86 ppm for every ppm of ammonia-N produced. Because this rate of change is so much greater for anaerobic conditions than for anoxic conditions alkalinity can be used to distinguish between the two. Thus, "septic" conditions can be avoided.

Alkalinity as a Process Control Indicator

Monitoring alkalinity within the treatment process can provide for the control of biological activity through adjustments to blower output, waste activated sludge rates and recycle rates.

The number and placement of sampling points are determined by the plant's size and processes design. A typical sampling layout might include the following sites:

- Primary Clarifier Influent
- Primary Clarifier Effluent
- Aeration Basin Influent
- Aeration Basin Effluent
- Secondary Clarifier Effluent
- Digester(s)

In primary clarifiers, solids are physically separated, thus biological activity and, by extension, alkalinity change is not expected. Increase in alkalinity indicates anoxic or anaerobic conditions in the sludge blanket. This could result in decreased removal efficiencies and increased organic and ammonia loading to the rest of the system. The remedy to this problem is to increase sludge removal- rates to decrease solids detention time in the sludge blanket.

The same principle applies to secondary clarifiers as with primary clarifiers. Significant alkalinity increase indicates the onset of anoxic denitrification. The remedy to this problem is to increase recycle sludge rates to decrease the solids detention time in the sludge blanket.

Comparing alkalinity in the aeration basin influent and effluent allows for optimized organic and ammonia removal (via nitrification). Insufficient alkalinity loss indicates poor ammonia removal and possibly turbid effluent. Increasing the air supply incrementally will help increase the nitrification rate. Significant nitrification may result in excessive alkalinity loss. This could result in lowered buffering capacity for the system and final effluent pH violations. Nitrification may also result in rising or denitrifying sludge in the secondary clarifier. Decreasing the air supply

and/or increasing the waste activated sludge rate (to decrease the solid retention time) will help remedy this problem.

Alkalinity decreases as bacteria aerobically metabolize organics. In an aerobic digester, sustained aeration may decrease alkalinity below the system's buffering capacity and cause the pH to drop low enough to limit biological activity. Consequently, poor settling and decreased volatile solids reduction may occur. The operator should establish high and low alkalinity "set-points" to maintain optimum digester efficiency. The aerobic digester should be aerated until alkalinity decreases to the low set-point. The operator should turn the air off to establish an anoxic cycle and avoid low pH levels. The dissolved oxygen will be depleted and nitrate will be used as the oxygen source during which alkalinity will correspondingly increase. The aeration is resumed when alkalinity reaches the high set-point to avoid septicity.

(Adapted from the February 1994 Operations Forum by Fred Dillon - Falmouth WPCF and Don Albert- MeDEP)

## APPENDIX W

### Seeded Biochemical Oxygen Demand Using Seeded Dilution Water

## Seeded Biochemical Oxygen Demand Using Seeded Dilution Water

### Background

*Biochemical oxygen demand (BOD)* is usually defined as the quantity of oxygen used by bacteria while stabilizing decomposable organic matter under aerobic conditions. The BOD test is conducted for a specific time interval, at a specified temperature, and under specific conditions. The standard BOO test is incubated in the dark for 5 days at  $20 \pm 1^\circ\text{C}$ . Because oxygen solubility is limited, strong waste must be diluted to ensure that dissolved oxygen (DO) is always present. Since the BOD test is a bioassay procedure, it is important that environmental conditions are always suitable for living organisms to function in an unhindered manner. This means that toxic substances must be absent and that necessary nutrients must be present. A diverse group of organisms is required to degrade organic matter biologically. Therefore it is important that a mixed group of microorganisms, commonly called "seed" be present in the test. Seeding is necessary when wastewater samples do not contain sufficient microorganisms. These viable microorganisms may not be present in industrial wastewater, or they may be killed by high temperature, extreme pH, or disinfecting chemicals. Typical domestic influent would not require seeding but final effluent which has been chlorinated and dechlorinated must always be seeded. When the "seed" is added, a small amount of organic material is also added which can have a measurable BOD itself. Therefore, a "seed correction factor" must be calculated.

### Introduction

BOD calculations can be confusing when it is necessary to use seeded dilution water. In Standard Methods, 16th Edition, page 531, the formula to be used with the seeded dilution water is written as follows:

$$\text{BOD}_{\text{mg/L}} = \frac{(D_1 - D_2) - (B_1 - B_2) \times f}{P} \quad \text{Eqn. 1}$$

where:

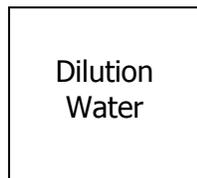
- $D_1$  = DO of diluted sample immediately after preparation, mg/L,
- $D_2$  = DO of diluted sample after 5 day incubation at  $20 \pm 1^\circ\text{C}$ , mg/L,
- $P$  = Decimal volumetric fraction of sample used,
- $B_1$  = DO of seed control before incubation, mg/L,
- $B_2$  = DO of seed control after incubation, mg/L, and
- $f$  = Ratio of seed in sample to seed in control  
= (% seed in D1)/(% seed in B1).

The most difficult variable to understand in Equation 1 is probably the f-factor. To obtain appropriate data for the calculation, the laboratory setup is critical. Proper laboratory setup for seeded BODs will be explained later in this article. First, the theory for the f-factor will be explained.

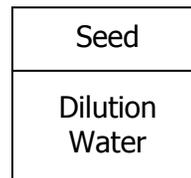
## Understanding the f-factor

A thorough understanding of the logic behind the f-factor is necessary to calculate seeded BOD. Standard Methods does not explain the f-factor in detail. The f-factor must be calculated to quantify the dissolved oxygen depletion due to the addition of seed. The following will illustrate the logic behind calculating f-factors.

A minimum of three bottles is required for quality control and representative seed control depletion. The first bottle is filled with dilution water only. Dilution water is distilled water plus the necessary nutrients. The second bottle is filled with a known volume of seed and dilution water. The third bottle is filled with seeded dilution water only. Seeded dilution water is made up of seed and dilution water. The remaining bottles contain different volumes of sample and seeded dilution water. To illustrate the theory, a fourth bottle is setup. The fourth bottle contains a certain volume of the wastewater to be tested and the remaining volume is filled with seeded dilution water.

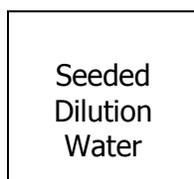


Bottle #1  
Blank Bottle  
Distilled Water  
+ Nutrients

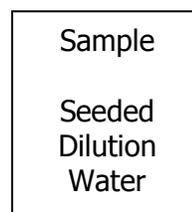


Bottle #2  
Seed Control Bottle

$$\begin{aligned} \text{Vol. seed} &= V_{\text{seed2}} \\ \text{Vol. DW} &= 300 - V_{\text{seed2}} \\ \text{Vol bottle} &= 300 \text{ mL} \end{aligned}$$



Bottle #3  
Blank Bottle  
Distilled Water  
+ Nutrients  
+ Seed



Bottle #4  
Sample Bottle

$$\begin{aligned} \text{Vol. sample} &= V_{\text{sample}} \\ \text{Vol. seeded DW} &= 300 - V_{\text{sample}} \\ \text{Vol. seed} &= (300 - V_{\text{sample}}) \times \text{SDW} \\ \text{Vol. DW} &= 300 - V_{\text{seed4}} - V_{\text{sample}} \end{aligned}$$

For the f-factor calculation, only bottle #2 and bottle #4 are needed. The other two bottles are quality control checks and they will be explained later. Standard Methods defines the f-factor as shown in the equation below.

$$f = \frac{\text{ratio of seed in the sample bottle}}{\text{ratio of seed in the seed control bottle}} \quad \text{Eqn. 2}$$

Using the variables in this example, the expression becomes:

$$f = \frac{V_{\text{seed4}} / \text{total volume of bottle \#4}}{V_{\text{seed2}} / \text{total volume of bottle \#2}} \quad \text{Eqn. 3}$$

If the total volume of Bottle #4 (300 mls) equals the total volume of Bottle #2 (300 mls), then

$$f = \frac{V_{\text{seed4}}}{V_{\text{seed2}}} \quad \text{Eqn. 4}$$

$$f = \frac{(300 - V_{\text{sample}}) \times (\text{seed concentration in dilution water})}{V_{\text{seed2}}} \quad \text{Eqn. 5}$$

The seed concentration in dilution water is the volume of seed per unit volume of dilution water.  $V_{\text{seed2}}$  is the volume of seed pipetted into the seed control bottle. The seed should be added to the dilution water rather than pipetting directly into the BOD bottles. Seed distribution is better and pipetting errors are reduced when seed is added to the dilution water. This is the proper technique.

By using Equation 5, the f-factor can be calculated. After substituting the calculated f-factor into Equation 1, the BOD of a particular sample can be calculated from the lab data.

### Laboratory procedure

Proper laboratory setup is critical in order to obtain valid data. The proper procedure for seeded BOD analysis is explained in detail in this section.

It is ideal to bring the sample temperature to 20°C. By placing the water tight sampling containers into a water bath, the sample can be warmed or cooled quickly.

Dilution water is prepared in the same manner as for unseeded BOD analysis. Sufficient distilled water must be at 20 ±1°C and aerated.

Sometimes the distilled water is stored in the BOD incubator for 24 hours to standardize the temperature. Do not add the nutrients before storing the distilled water. Add the nutrients prior to setting up BOD samples. Be sure to allow sufficient time for the nutrients to dissolve. Swirl the container for mixing. The mixture is now called standard dilution water. Fill Bottle #1 with this dilution water completely. This is called the blank and is used to provide quality assurance for this analysis.

The second bottle is prepared by filling the BOD bottle with standard dilution water to approximately halfway first. Pipette a known volume of seed into the BOD bottle and then fill the bottle with dilution water. In this example, five milliliters of seed are pipetted into the bottle. This is called the seed control bottle.

After the first two bottles are set up, seed is added to the dilution water. Three milliliters of seed per liter of dilution water is the ratio used for this example. Swirl the mixture gently making sure not to over agitate the mixture. Swirling will prevent further aeration and avoid over-saturating the seeded dilution water with dissolved oxygen. Bottle #3 is completely filled with this seeded dilution water.

Seed can be obtained from several locations within the wastewater treatment facility. Settled domestic influent and secondary clarifier effluent are two of the most popular sources of seed. Also artificial seed can be purchased from some laboratory supply houses. The preferred seed is effluent from a biological treatment plant treating the waste. If the choice of seed is the influent domestic wastewater, allow the seed to settle for at least 1 hour but no more than 36 hours at 20°C. Consistent settling time is ideal in this case.

Dechlorinate the samples to neutralize the chlorine residual, if necessary, at this point. Dechlorination can be accomplished by adding sodium sulfite ( $\text{Na}_2\text{SO}_3$ ), or a dechlorinating tablet purchased from supply houses can be utilized. The volume of sodium sulfite required must be determined by titrating with 0.025N  $\text{Na}_2\text{SO}_3$  to the starch-iodine end point. The temperature of the samples should now be about 20°C. Samples which are alkaline or acidic must be neutralized to a pH of 6.5 to 7.5 with a solution of sulfuric acid or sodium hydroxide.

The next step in the BOD setup process is to estimate the BOD of the sample. As a guide, typical domestic influent wastewater has a BOD of about 200 to 300 mg/L. Secondary wastewater treatment effluent has a BOD of about 5 to 50 mg/L. For most wastewater analysis, three sample dilutions are setup for each sample to be tested. For the influent sample, typically 3, 6, and 9 milliliters of sample into a 300 milliliter BOD bottle should provide sufficient range. Referring to the Table 1 on the next page, this influent setup covers a BOD range from 70 to 560 mg/L. As for the effluent sample, 24, 50, and 100 milliliter sample are chosen. This volume selection covers a BOD range from 6 to 70 mg/L.

After you have chosen the dilutions to setup, fill the remaining BOD bottles allocated for receiving samples to about a quarter of the total volume with seeded dilution water. These BOD bottles are ready to receive wastewater samples. Before the samples are transferred to their respective BOD bottles, each sample must be thoroughly mixed.

It is important to mix the sample bottle by shaking vigorously (not only stirred) before pipetting any sample from the sample bottle to the BOD bottle to ensure homogeneous transfer of sample. The BOD bottles are then filled up with the seeded dilution water. After measuring initial DO, the BOD bottles are then sealed with glass stoppers, water sealed, and capped with plastic covers before incubation. Make sure that there are no air bubbles trapped in the BOD bottles. Top off with dilution water, if necessary, to eliminate air bubbles.

Table 1

| Expected BOD Range            |             |             |
|-------------------------------|-------------|-------------|
| Sample added to 300-ml bottle | Min. (mgjL) | Max. (mgjL) |
| 3                             | 210         | 560         |
| 6                             | 105         | 280         |
| 9                             | 70          | 187         |
| 12                            | 53          | 140         |
| 15                            | 42          | 112         |
| 18                            | 35          | 94          |
| 21                            | 30          | 80          |
| 24                            | 26          | 70          |
| 27                            | 24          | 62          |
| 30                            | 21          | 56          |
| 50                            | 12          | 42          |
| 75                            | 8           | 22          |
| 100                           | 6           | 21          |
| 150                           | 4           | 12          |

The results for this example after 5-day incubation are presented in Table 2. The lab prepared three different dilutions each for influent and effluent samples.

TABLE 2 - Lab Results

| Bottle Number | Sample Volume         | Initial DO | Final DO | DO Depleted | BOD Mg/L |
|---------------|-----------------------|------------|----------|-------------|----------|
| 1             | dilution water        | 9.05       | 9.00     | 0.05        | -        |
| 2             | seed control          | 8.90       | 3.30     | 5.60        | 336      |
| 3             | seeded dilution water | 8.95       | 7.95     | 1           | -        |
| Influent      |                       |            |          |             |          |
| 4             | 3 mL                  | 8.95       | 5.95     | 3.00        | 201      |
| 5             | 6 mL                  | 8.85       | 3.75     | 5.10        | 206      |
| 6             | 9 mL                  | 8.85       | 1.25     | 7.60        | 221      |
| Effluent      |                       |            |          |             |          |
| 7             | 24 mL                 | 7.75       | 4.25     | 3.5         | 32       |
| 8             | 50 mL                 | 7.8        | 5.0      | 2.8         | 12       |
| 9             | 100 mL                | 7.8        | 7.3      | 0.5         | -        |

Standard Methods recommends that the following criteria are met for BOD analysis. When performing the dilution water check, DO depletion in the blank should not exceed 0.2 mg/L and preferably not more than 0.1 mg/L. In this case, DO depletion for the blank is 0.05 mg/L; therefore it meets the first criterion. If the blank depletion of your test is greater than 0.2 mg/L, you must not subtract this depletion from the BOD depletion. Normally, dirty glassware, contaminated nutrients, contaminated distilled water, and contamination from handling the water can contribute to this problem. Therefore, it is important to clean the glassware after use, dry BOD bottles with the mouths facing downwards and avoid any contact with the hands when aerating the distilled water. Place a piece of laboratory film with the clean side facing the mouth of the dilution bottle to eliminate any contact with the palm during aeration. If you must temperature equalize the distilled water in the incubator, pierce a few holes through the laboratory film and leave the laboratory film in place as a cover. These precautionary steps described above should help to eliminate this problem. If the problem persists, then it normally can be resolved by improving the quality of the lab water used to prepare the dilution water and perhaps a new batch of nutrients. The lab distillation apparatus may need cleaning, for example.

The seeded dilution water has depleted 1 mg/L of oxygen. This indicates good seed source. This depletion needs to be accounted for in the BOD calculations. Standard Methods recommends that the seeded dilution water depletion should be between 0.6 mg/L and 1.0 mg/L. If there is no depletion after 5-day incubation, then the seed could be bad or the seed volume must be increased until the criterion is met.

The DO depletion in the seed control should be at least 2 mg/L and must have 1 mg/L residual after the 5-day incubation. If the seed control depletes all of the DO, then the seed is excellent but the volume of seed pipetted into the BOD bottle has to be reduced. In this example, Bottle #2 depleted 5.6 mg/L of dissolved oxygen and had 3.3 mg/L of DO residual after 5 days of incubation. Therefore, it satisfies this criterion.

Moving along in the table, you will notice that the initial DO concentrations for the influent dilutions are approximately the same. Another observation is that the water is not super-saturated with oxygen. At 20°C, the solubility of oxygen in water at atmospheric pressure is about 9.1 mg/L. Therefore, you can use this as a guide for initial DO concentration and take care not to exceed this concentration.

The next consideration is checking for at least 2 mg/L of DO depletion and a DO residual of at least 1 mg/L after 5-day incubation. Bottle #9 did not meet both requirements as it has only 0.5 mg/L of DO residual. The remaining bottles did meet these two criteria. Any bottles that do not have 2 mg/L depletion and 1 mg/L residual after 5-day incubation should be deleted from BOD calculations.

Now we can calculate the BOD for each sample dilution. First we have to determine the f-factor for each valid test using Equation 5. The bottle volume and seed concentration in the seed control are shown for purposes of clarity only.

$$\begin{aligned}f_4 &= (300-3) (3/1000) / (300) (5/300) = 0.1782 \\f_5 &= (300-6) (3/1000) / (300) (5/300) = 0.1764 \\f_6 &= (300-9) (3/1000) / (300) (5/300) = 0.1746 \\f_7 &= (300-24) (3/1000) / (300) (5/300) = 0.1656 \\f_8 &= (300-50) (3/1000) / (300) (5/300) = 0.15\end{aligned}$$

The BOD for each valid dilution can now be determined using Equation 1.

$$\begin{aligned}\text{BOD}_4 &= (8.95-3.30) - (8.90-3.30) (0.1782) / (3/300) = 200 \text{ mg/L} \\ \text{BOD}_5 &= (8.85-3.75) - (8.90-3.30) (0.1764) / (6/300) = 206 \text{ mg/L} \\ \text{BOD}_6 &= (8.85-1.25) - (8.90-3.30) (0.1746) / (9/300) = 221 \text{ mg/L} \\ \text{BOD}_7 &= (7.75-4.25) - (8.90-3.30) (0.1656) / (24/300) = 32 \text{ mg/L} \\ \text{BOD}_8 &= (7.80-5.00) - (8.90-3.30) (0.1500) / (50/300) = 12 \text{ mg/L}\end{aligned}$$

Effluent BOD shows a decreasing trend as the sample volume increases. This indicates toxicity in the sample. If this type of decreasing trend occurs consistently in your BOD testing, then the source of possible toxicity must be identified. In this example, the toxic substance could be from an in-plant source because influent BOD testing does not show a decreasing trend as sample volumes increase.

The actual BOD for each sample should be the average of all of the satisfactory tests. In this example, the influent BOD is 209 mg/L and effluent BOD is 22 mg/L.

It is important to note that the DO depletion in the seed control cannot be used in the BOD computation directly without first considering the f-factor like the example shown in this article. The f-factor decreases as the sample volume increases.

Data from our example was used with a second formula which was obtained from Simplified Laboratory Procedures for Wastewater Examination, Second Edition. This was to verify that the BOD result obtained from either formula is identical. The formula modified for seeded BOD is as follows:

$$BOD_5 = \left[ (D_1 - D_2) - \frac{(L) \times (BOD_{seed})}{300} \right] \times \left[ \frac{300}{\text{sample volume}} \right] \quad \text{Eqn. 6}$$

where,

- L = Volume of seed in the bottle that contained sample
- D1 = DO of diluted sample immediately after preparation, mg/L,
- D2 = DO of diluted sample after 5 day incubation at 20 °e, mg/L,
- BOD<sub>seed</sub> = Calculated BOD for the seed control, mg/L.

The following will show the BOD computation using a modification of Equation 6 which deletes the seed correction step. This is possible because the seed control bottle measures the BOD of the seed material directly.

$$BOD_{seed} = ((B_1 - B_2) / (\text{Volume of seed})) \times 300$$

$$BOD_{seed} = ((8.9 - 3.3) / (5)) \times 300$$

$$BOD_{seed} = 336$$

where,

- B1 = DO of seed control before incubation, mg/L,
- B2 = DO of seed control after incubation, mg/L.

The volume of seed transferred from the seeded dilution is calculated by multiplying the volume of seeded dilution water to fill the BOD bottle with the seed concentration used.

$$L_4 = (300 - 3 / 1000) = 0.891 \quad L_7 = (300 - 24) (3 / 1000) = 0.828$$

$$L_5 = (300 - 6) (3 / 1000) = 0.882 \quad L_8 = (300 - 50) (3 / 1000) = 0.750$$

$$L_6 = (300 - 9) (3 / 1000) = 0.873$$

$$BOD_4 = \left[ (8.95 - 5.95) - \frac{(0.891) \times (336)}{300} \right] \times \left[ \frac{300}{3} \right] = 200 \text{ mg/L} \quad \text{Similarly,}$$

$$BOD_5 = 206 \text{ mg/L} \quad BOD_7 = 32 \text{ mg/L}$$

$$BOC_6 = 221 \text{ mg/L} \quad BOD_8 = 12 \text{ mg/L}$$

Note that using either formula will produce the same BOD results. The analyst must understand how to properly use whichever formula is chosen.

## **Glucose-Glutamic Acid BOD quality check**

This is a check on possible toxicants and seed source reliability. For example, distilled water could be contaminated by copper and the seed could be relatively inactive. These factors can often yield lower BOD results. Therefore, by measuring BOD on pure organic compounds, dilution water quality, seed reliability and analytical technique can be checked.

This test is done using standard BOD equipment. The only additional items are the chemicals. For each test, dissolve 150 milligrams of glucose and 150 milligrams of glutamic acid into 500 milliliters of distilled water in a one liter volumetric flask. Add sufficient distilled water to make exactly one liter of solution. Seal the flask with laboratory film and mix the solution by tipping a few times. Make sure all of the chemicals are dissolved.

Partially fill a BOD bottle with seeded dilution water. Add 6 milliliters of the glucose-glutamic acid solution from the one liter flask to the BOD bottle. Then complete filling the BOD bottle with seeded dilution water. Take an initial DO reading of this bottle and incubate for 5 days at  $20 \pm 1^\circ\text{C}$ . Take another DO reading after 5 days. The BOD for the glucose-glutamic acid standard can then be determined.

This 2 percent glucose-glutamic acid solution should yield a BOD of  $200 \pm 37$  mg/L. If the BOD does not fall within this range, find the possible source of errors, correct the problems, and try the test again. It should deplete at least 2 mg/L of dissolved oxygen and leave at least 1 mg/L dissolved oxygen residual after 5-day incubation. Remember to take the seed depletion into account when calculating the glucose-glutamic acid BOO. This means that the factor must be determined first and then the BOD.

Never attempt to store the glucose-glutamic acid solution for the next test. Always make up new batch of solution for every test. The glucose-glutamic acid check should be done according to a schedule adopted as part of the facility's laboratory QA/QC plan.