Wastewater Microbiology Series

Settleability Problems and Loss of Solids in the Activated Sludge Process

MICHAEL H. GERARDI

Environmental PROTECTION Magazine Series

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WILEY-INTERSCIENCE

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To
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Contents

Preface

The activated sludge process is the most versatile and most commonly used wastewater treatment system in North America. Although the activated sludge process is capable of efficiently treating municipal and industrial wastewaters, many activated sludge processes frequently experience operational problems related to poor compaction or settleability of secondary solids and loss of secondary solids from the clarifier. Operational problems associated with settleability problems and loss of solids include increased operational costs, loss of treatment efficiency, and permit violations.

Because the activated sludge process is a biological wastewater treatment system, settleability problems and loss of solids are reviewed through undesired changes in activity and structure of the biomass—floc particles, protozoa, and metazoa. With the use of numerous tables and illustrations, this book describes the operational conditions responsible for settleability problems and loss of solids—including foam and scum production. The book also provides microscopic and analytical techniques for identifying and troubleshooting the conditions responsible for settleability problems and loss of solids. Pictures of wet mounts and smears of acceptable and unacceptable microscopic conditions of the activated sludge are included. Corrective measures for the operational conditions responsible for settleability problems and loss of solids are presented.

This book is prepared for an audience of operators and technicians who are responsible for the daily operation of the activated sludge process. The book is written for troubleshooting and process control of the activated sludge process in efforts to reduce operational costs, maintain treatment efficiency, and prevent permit violations.

Settleability Problems and Loss of Solids in the Activated Sludge Process is the second book in the Wastewater Microbiology Series by John Wiley & Sons. This

series is designed for operators and technicians and provides a microbiological review of the organisms involved in wastewater treatment, their beneficial and detrimental roles, and the biological techniques available for operators to monitor and regulate the activities of these organisms.

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Part I

Overview

1

The Activated Sludge Process

The activated sludge process is the most commonly used treatment system for municipal and industrial wastewaters in North America. The activated sludge process consists of at least one aeration tank or aeration period and one sedimentation tank or settling period (Figure 1.1). The sedimentation tank is also known as a clarifier and is located downstream from the aeration tank. Many activated sludge processes have a clarifier upstream of the aeration tank. If the activated sludge process has a clarifier upstream of the aeration tank, this clarifier is the primary clarifier and the clarifier downstream of the aeration tank is the secondary clarifier.

The aeration tank is a biological reactor or amplifier in which wastes are converted through the activity of microscopic organisms to less polluting wastes or nonpolluting wastes and more solids or microscopic organisms, mostly bacterial cells. The secondary clarifier is a quiescent environment that permits the separation of solids from its suspending medium (water). The secondary clarifier also removes floating foam and scum produced in and discharged from the aeration tank. The primary clarifier permits the separation and removal of floatable materials and settleable solids.

The solids in the activated sludge process are also known as sludge. Bacteria represent a significant portion of the sludge. Because the sludge is aerated, the bacteria become very active in the degradation and removal of wastes. Therefore, the term "activated sludge" is used to describe the process in which bacterial solids are active in the treatment or purification of wastes.

The activated sludge process is capable of performing four critical wastewater treatment functions (Table 1.1). These functions are 1) the degradation or oxidation of carbonaceous wastes (Figure 1.2), 2) the degradation or oxidation of nitrogenous wastes (Figure 1.3), 3) the removal of "fine" solids, and 4) the removal of "heavy" metals.

Organic wastes are chemical compounds that contain carbon (C) and hydrogen (H) and represent the carbonaceous biochemical oxygen demand (cBOD) placed

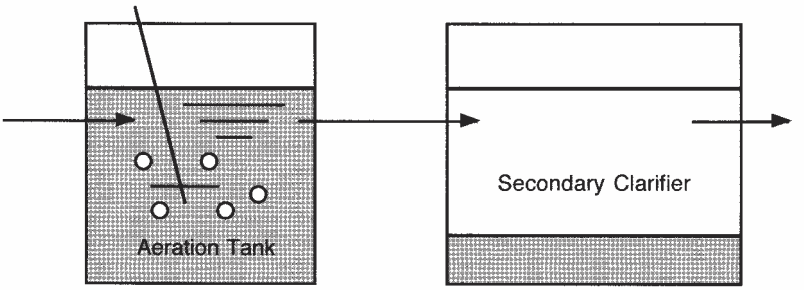

Figure 1.1 *Basic units of the activated sludge process. The activated sludge process contains at least one aeration tank or aeration period and one sedimentation tank or settling period. The sedimentation tank is also known as a clarifier. The aeration tank is a turbulent environment in which bacteria (floc particles) are mixed with air (dissolved oxygen) and incoming wastewater. Bacterial use of dissolved oxygen permits the degradation of the carbonaceous wastes (cBOD) and nitrogenous wastes (nBOD) within the wastewater. The floc particles remain in the activated sludge process if the floc particles settle out in the clarifier. The clarifier is a quiescent environment in which floc particles settle out of their suspending medium (water). The settled bacteria are referred to as the sludge blanket. The clarifier is always downstream of the aeration tank. If a clarifier is located upstream of the aeration tank, the clarifier upstream of the aeration tank is the primary clarifier and the clarifier downstream of the aeration tank is the secondary clarifier.*

TABLE 1.1 Critical Wastewater Treatment Functions of the Activated Sludge Process

Function	Oxidation Equation or Components Removed
Oxidation of cBOD	cBOD (protein) + $O_2 \rightarrow C_5H_7O_2N$ (cells) + CO_2 + H_2O + NH_4^+ + SO_4^{2-} + HPO_4^{2-}
Oxidation of nBOD	nBOD (ammonium ions) + $O_2 \rightarrow C_5H_7O_2N$ (cells) + NO_3^- + H_2O
Removal of "fine" solids	Colloids, dispersed growth, and particulate materials
Removal of "heavy" metals	Aluminum, chromium, copper, cadmium, iron, lead, mercury, nickel, zinc, etc.

on an activated sludge process (Table 1.2). Nitrogenous wastes are chemical compounds that contain nitrogen (N) (Table 1.3). When nitrogenous compounds are degraded in an activated sludge process, ammonium ions (NH_4^+) may be released. Ammonium ions released in the activated sludge process or discharged to the activated sludge process represent a significant portion of the nitrogenous biochemical oxygen demand (nBOD) placed on an activated sludge process. The remaining portion of the nBOD is represented by nitrite ions (NO_2^-). These ions may be discharged to the activated sludge process by industries (Table 1.4) or may be produced in the activated sludge process when ammonium ions are oxidized or nitrified (Equation 1.1). When ammonium ions are oxidized, oxygen is added to the ammonium ions.

$$NH_4^+ + 1.5O_2 \rightarrow 2H^+ + NO_2^- + H_2O \tag{1.1}$$

Biochemical oxygen demand (BOD) is the amount of oxygen (mg/l) consumed by microorganisms, primarily bacteria, to degrade organic wastes and nitrogenous wastes over a fixed period of time, usually 5 days. BOD contains cBOD and nBOD.

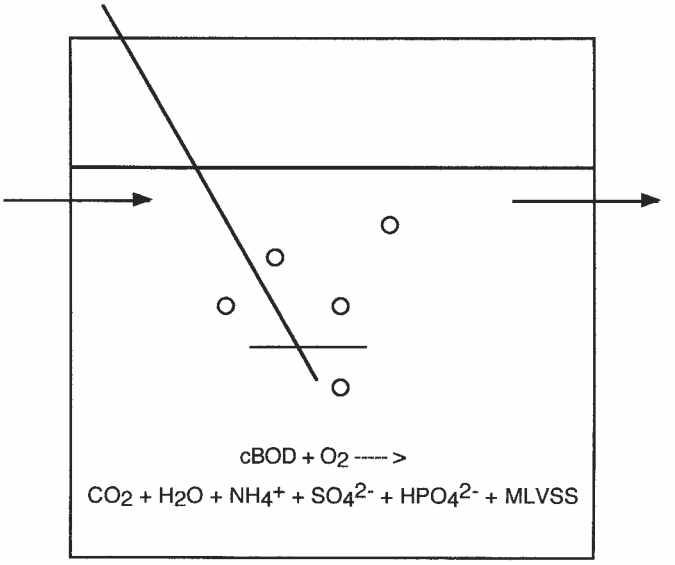

Figure 1.2 *Oxidation of carbonaceous wastes (cBOD). In the aeration tank, influent carbonaceous wastes (cBOD) such as alcohols, amino acids, organic acids, proteins, and sugars are oxidized into nonpolluting wastes and less polluting wastes. Nonpolluting wastes are carbon dioxide (CO_2) and water (H_2O). Less polluting wastes are ammonium ions (NH_4^+), sulfate ions (SO_4^{2-}), orthophosphate ions (HPO_4^{2-}), and new bacteria cells or sludge (MLVSS).*

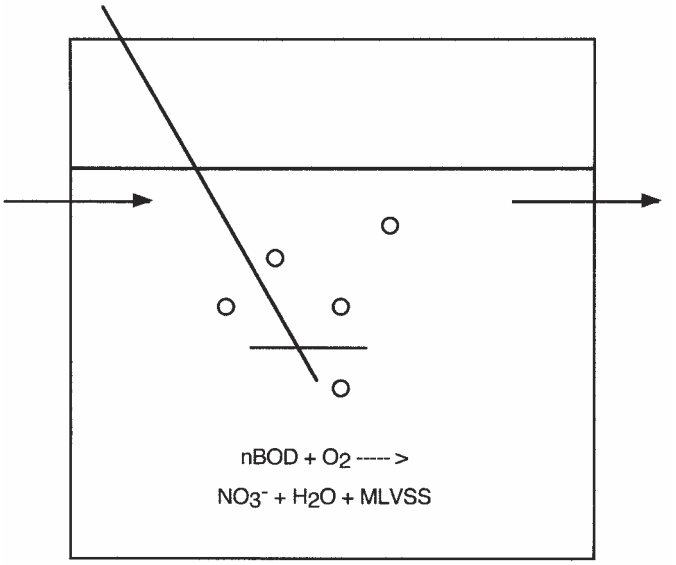

Figure 1.3 *Oxidation of nitrogenous wastes (nBOD). In the aeration tank, influent nitrogenous wastes (nBOD) are oxidized into nonpolluting wastes and less polluting wastes. Nitrogenous wastes that are oxidized in the aeration tank include ammonium ions (NH_4^+) and nitrite ions (NO_2^-). The nonpolluting waste produced from the oxidation of nBOD is water (H_2O), whereas the less polluting wastes produced from the oxidation of nBOD are nitrate ions (NO_3^-) and new bacterial cells or sludge (MLVSS).*

TABLE 1.2 Examples of Organic Compounds that Contribute to cBOD

Organic Compound	Chemical Formula	Common Name
Acetic acid	CH_3COOH	Vinegar
Ethanol	CH_3CH_2OH	Alcohol
Glucose	$C_6H_{12}O_6$	Sugar

TABLE 1.3 Examples of Nitrogenous Compounds

Nitrogenous Compound	Chemical Formula	Common Name
Glycine (amino acid)	NH_2CH_2COOH	Glycine
Nitric acid	HNO_3	Nitric acid
Urea	H_2NCONH_2	Urea

TABLE 1.4 Industrial Dischargers of Ammonium Ions (NH_4^+) and Nitrite Ions (NO_2^-)

Industrial Discharger	NH_4^+	NO_2^-
Automotive	X	
Chemical	X	
Coal	X	
Corrosion inhibitor		X
Fertilizer	X	
Food		X
Leachate	X	
Leachate (pretreated)		X
Livestock	X	
Meat	X	
Meat (preservative)		X
Ordnance	X	
Petrochemical	X	
Pharmaceutical	X	
Primary metal	X	
Refineries	X	
Steel	X	X
Tanneries	X	

Organotrophic bacteria remove oxygen from the wastewater to degrade cBOD, and nitrifying bacteria remove oxygen from the wastewater to degrade nBOD.

Organotrophic bacteria obtain their energy and carbon for life by oxidizing cBOD. Nitrifying bacteria obtain their energy for life by oxidizing ammonium ions and nitrite ions or nBOD (Equations 1.2 and 1.3). Nitrifying bacteria obtain their carbon for life by removing bicarbonate alkalinity (H_2CO_3) from the wastewater.

$$NH_4^+ + 1.5O_2 \text{ — Nitrifying bacteria} \rightarrow 2H^+ + NO_2^- + H_2O \tag{1.2}$$

$$NH_4^+ + 2O_2 \text{ — Nitrifying bacteria} \rightarrow NO_3^- + 2H^+ + H_2O \tag{1.3}$$

The activated sludge process can efficiently remove colloids, dispersed cells, particulate materials, and heavy metals from a waste stream. Colloids, dispersed

cells, and particulate materials make up the "fine" solids in the activated sludge process.

Colloids are relatively large and complex molecules that vary in size from 1 to 100 nm. These molecules do not dissolve in wastewater. Because of their large surface area, colloids remain suspended in the wastewater. Examples of colloids are proteins that are found in domestic, dairy, and meat processing wastes.

Dispersed cells consist of microscopic unicellular organisms such as algae, bacteria, and fungi that are suspended in the wastewater because of their buoyant nature or motility. These organisms may be found as individual cells or as small aggregates of cells. Dispersed growth is considered to be $<5\,\mu m$ in size and consists mostly of bacterial cells.

Particulate materials are inert or nonliving wastes and are considered to be $\geq 5\,\mu m$ in size. Particulate materials may be found in a variety of colors and shapes, and much particulate material remains suspended in the wastewater because of its buoyant nature. Particulate materials that do not settle out in the primary clarifier enter the activated sludge process. Particulate materials such as cellulose, an insoluble starch, may be degraded in the activated sludge process if sufficient hydraulic retention time (HRT) (Appendix I) is provided in the aeration tank.

Heavy metals commonly enter most activated sludge processes in the soluble form. Examples of soluble heavy metals include the metal ions copper (Cu^{2+}), nickel (Ni^{2+}), and zinc (Zn^{2+}). The activated sludge process quickly and efficiently removes heavy metals.

Fine solids and heavy metals are removed from a waste stream by the activated sludge process. Their removal is achieved through their adsorption to bacterial cells and the activity of ciliated protozoa and metazoa (animals) or higher life forms (Figure 1.4). The most commonly occurring metazoa in the activated sludge process are rotifers and free-living nematodes.

The ability of the activated sludge process to degrade BOD and remove fine solids and heavy metals is achieved primarily through the growth and maintenance of a large, diverse, and active population of bacteria. The growth in numbers and diversity of bacteria occurs over time or increasing mean cell residence time (MCRT) or sludge age (Appendix I) as BOD is transformed into new bacterial cells or sludge. The bacterial population is maintained in the activated sludge process through the development of firm and dense mature floc particles (Figure 1.5). The development of floc particles is known as floc formation.

Two important characteristics of the floc particle determine the treatment efficiency of the activated sludge process to degrade BOD and remove fine solids and heavy metals. These characteristics are the activity of the floc bacteria and the structure of the floc particle (Figure 1.6). Because these characteristics determine treatment efficiency, they also affect operational costs and compliance with state and federal permit discharge limitations.

Activated sludge processes that have two or more aeration tanks may be designed to operate in a variety of schemes or modes of operation. The feed points of primary clarifier effluent or activated sludge influent and return activated sludge (RAS) determine the mode of operation of an activated sludge process. The RAS refers to the solids removed from the secondary clarifier and returned to the aeration tanks. Modes of operation include complete mix, plug-flow, step feed, and contact stabilization (Figure 1.7).

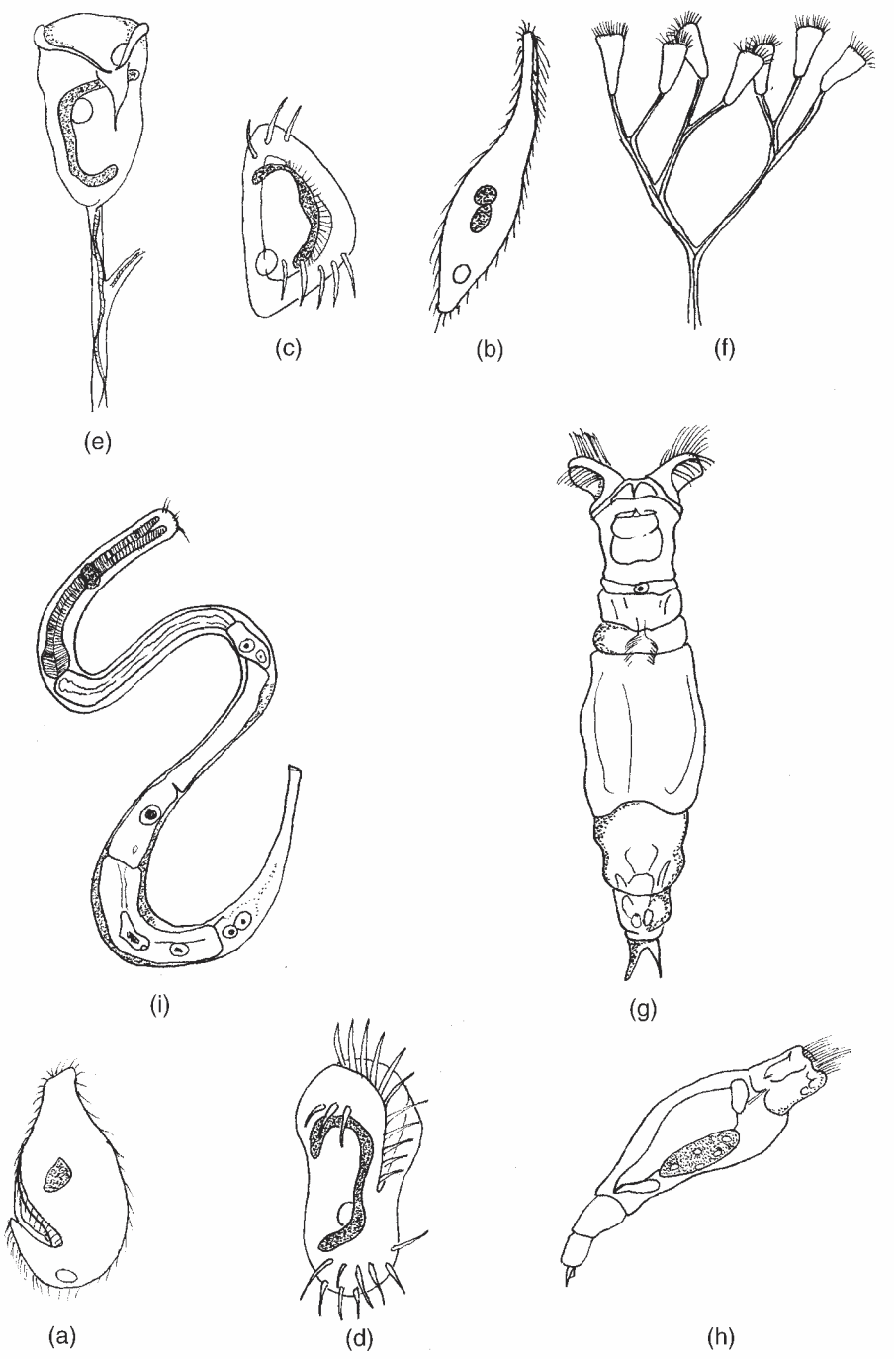

Figure 1.4 *Commonly observed ciliated protozoa and metazoa. Commonly observed ciliated protozoa and metazoa in the activated sludge process include the free-swimming ciliates* Blepharisma *(a) and* Litonotus *(b); the crawling ciliates* Aspidisca *(c) and* Euplotes *(d); and the stalked ciliates* Carchesium *(e) and* Zoothamnium *(f). Metazoa include the rotifers* Philodina *(g) and* Pleurotrocha *(h) and free-living nematodes (i).*

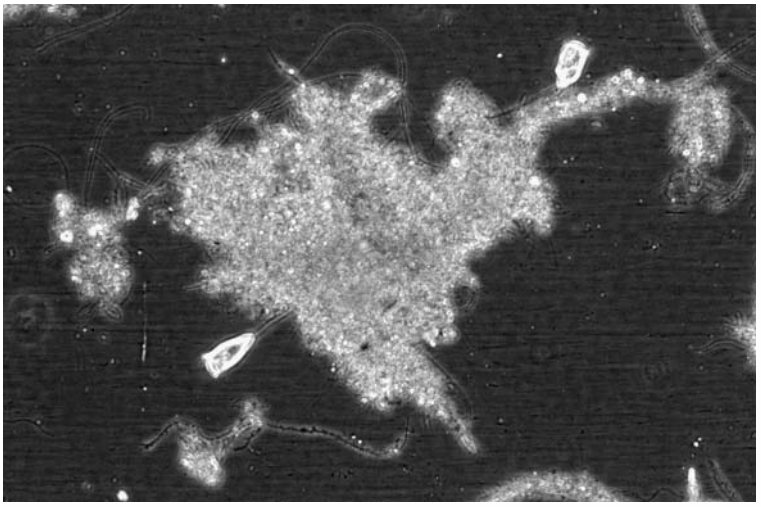

Figure 1.5 *Firm and dense floc particles. In an old sludge age system, firm and dense floc particles are developed. The floc particles are irregular in shape because of the presence of filamentous organism, usually large (>500μm) in size and dark in color because of the accumulation of biological oils.*

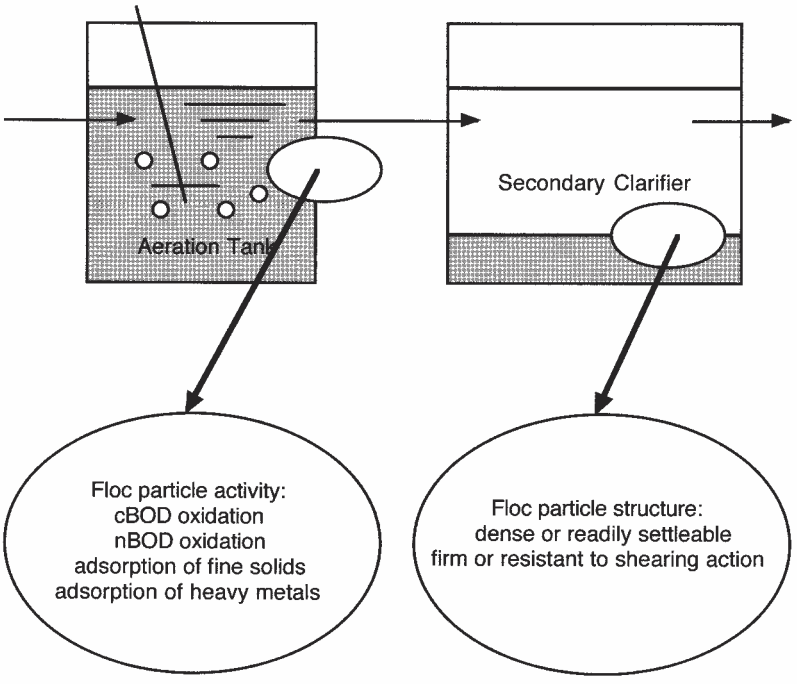

Figure 1.6 *Importance of floc particle activity and floc particle structure. Proper activity and proper structure of the floc particle in the activity sludge process are critical to its success. Proper activity of the floc particle ensures adequate oxidation of cBOD and oxidation of nBOD in the aeration tank. Proper activity also ensures adequate removal of fine solids and heavy metals in the aeration tank. Proper structure provides for dense floc particles that are readily settleable in the secondary clarifier. Proper structure also provides for firm floc particles that are resistance to shearing action. Proper floc particle structure prevents settleability problems and loss of solids.*

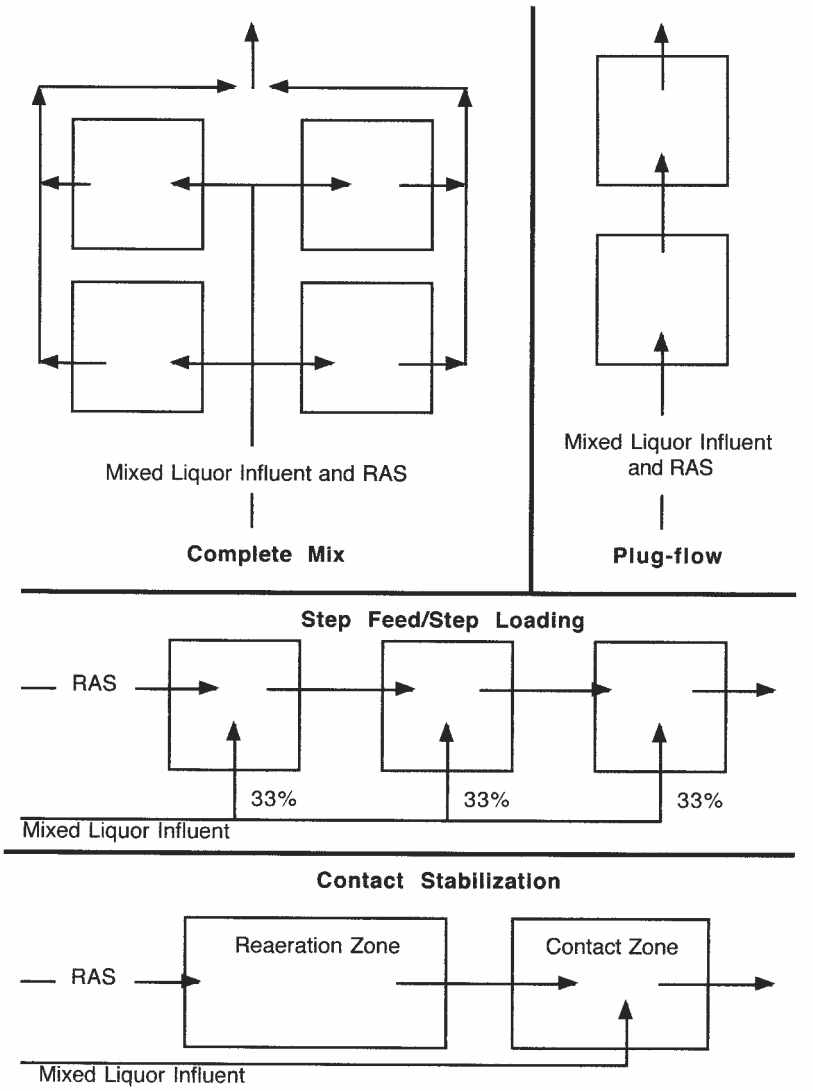

Figure 1.7 *Modes of operation. Several modes of operation are commonly used in the activated sludge process. These modes of operation include complete mix, plug-flow, step feed or step loading, and contact stabilization. Each mode of operation has unique flow patterns that distribute the mixed liquor influent (primary clarifier effluent) and RAS to the aeration tanks for treatment.*

There are two commonly used variations of the activated sludge process that do not permit the use of complete mix, plug-flow, step feed, and contact stabilization modes of operation. These variations are the oxidation ditch (Figure 1.8) and the sequential batch reactor (SBR) (Figure 1.9). The oxidation ditch uses a circular flow pattern for the treatment of wastewater, whereas the SBR has only one tank that uses a period of time for aeration that is followed by a period of time for settling of solids.

Bacteria are suspended in the aeration tank through mixing action and aeration. The bacteria are present in the aeration tank in floc particles in billions per gram

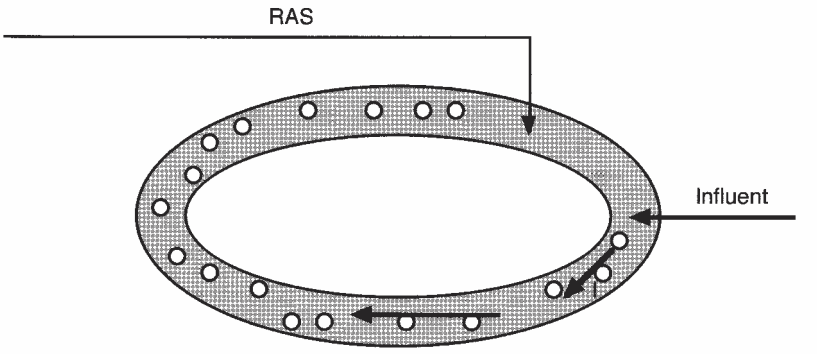

Figure 1.8 *Oxidation ditch. The oxidation ditch has a circular flow pattern for the distribution and treatment of influent wastewater.*

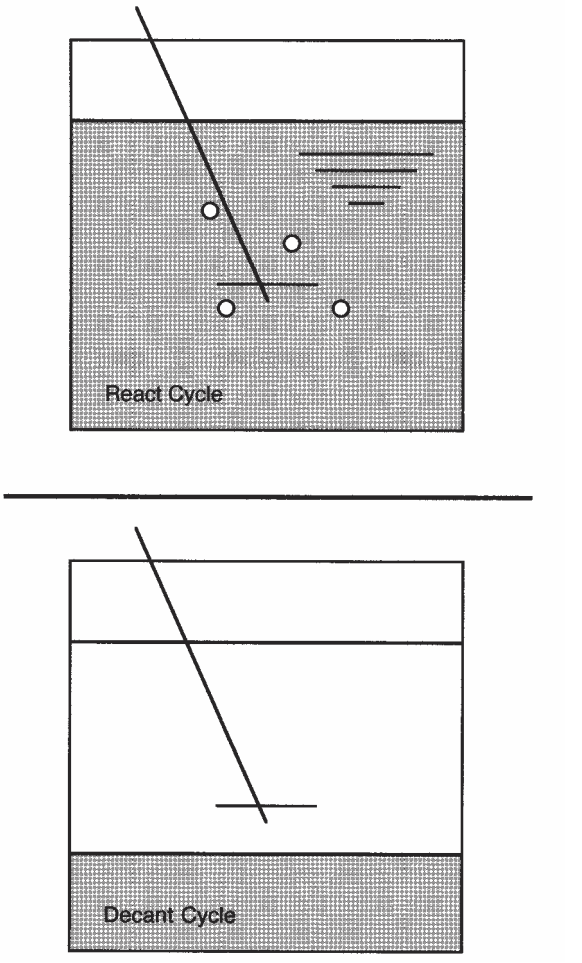

Figure 1.9 *Sequential batch reactor. The sequential batch reactor or SBR is a treatment tank that uses time periods for the treatment of wastewater. During the first period or fill period, wastewater enters the nonaerated tank. During the second period or react period, the wastewater is mixed and aerated with the floc particles or bacteria in the tank. During the third period or settling period, mixing action and aeration are stopped and the floc particles are separated from their suspending medium through a quiescent settling period. During the fourth or decant period, the supernatant is drawn off the settled solids. After the decant period, the fill period begins again.*

and in the bulk solution in millions per milliliter. The sludge or bacteria in the aeration tank are also known as mixed liquor volatile suspended solids (MLVSS) or mixed liquor. The MLVSS is used to describe the population size of bacteria, because the bacteria are mixed with waste streams or liquors (RAS and activated sludge influent) and are volatile suspended solids.

Because it is time consuming and expensive to perform detailed microbiological techniques to determine the number of bacteria in an activated sludge process, an estimate of the population size of the bacteria is made by determining the MLVSS (Appendix I). An increase in MLVSS is considered to be an increase in the population size of the bacteria, and a decrease in MLVSS is considered to be a decrease in the population size of the bacteria.

The bacteria degrade and transform the BOD to less polluting wastes, nonpolluting wastes, and more bacterial cells or MLVSS. The bacteria, along with ciliated protozoa and metazoa, remove fine solids and heavy metals from the bulk solution. An additional and critical role performed by the ciliated protozoa and metazoa is the consumption of dispersed cells. Ciliated protozoa and metazoa consume bacteria as a food source. The consumption of dispersed bacteria by these organisms is known as cropping action. By cropping bacteria, the bacteria are removed from the waste steam.

In the activated sludge process, wastes are converted to less polluting wastes and nonpolluting wastes. Less polluting wastes such as NH_4^+, SO_4^{2-}, and HPO_4^{2-} may contribute to operational problems or environmental problems depending on the fate of the wastes. Ammonium ions may be nitrified in the activated sludge process and contribute to increased operational costs through increased aeration or denitrification problems in the secondary clarifier. Sulfate ions may contribute to malodor production, if they are reduced through bacterial activity to hydrogen sulfide (H_2S) in the secondary clarifier or thickener. Orthophosphate ions in the final effluent may contribute to undesired algal blooms or undesired, rapid growth of aquatic plants in the receiving stream.

Nonpolluting wastes consist of H_2O and CO_2. Water is discharged to the receiving stream, whereas carbon dioxide either escapes to the atmosphere or dissolves in the wastewater to form bicarbonate ions.

The secondary clarifier is a quiescent environment in which floc particles are separated from their suspending medium or the bulk solution. The settled floc particles make up the settled solids or sludge blanket of the secondary clarifier. Solids in the sludge blanket may be returned to the aeration tank to treat more wastewater or may be removed (wasted) from the activated sludge process for further treatment and disposal. The solids returned to the aeration tank are the return activated sludge (RAS), and the solids wasted from the activated sludge process are the waste activated sludge (WAS) (Figure 1.10).

Regardless of the mode of operation or variation of the activated sludge process used, the activated sludge process is dependent on floc particles for the degradation of BOD and removal of fine solids and heavy metals. If proper floc formation does not occur, settleability problems and loss of solids usually occur. If proper floc formation does not occur, increased operational costs and permit violations also occur.

Proper floc formation does not occur when an undesired change in bacterial activity or floc particle structure occurs. An undesired change in bacterial activity

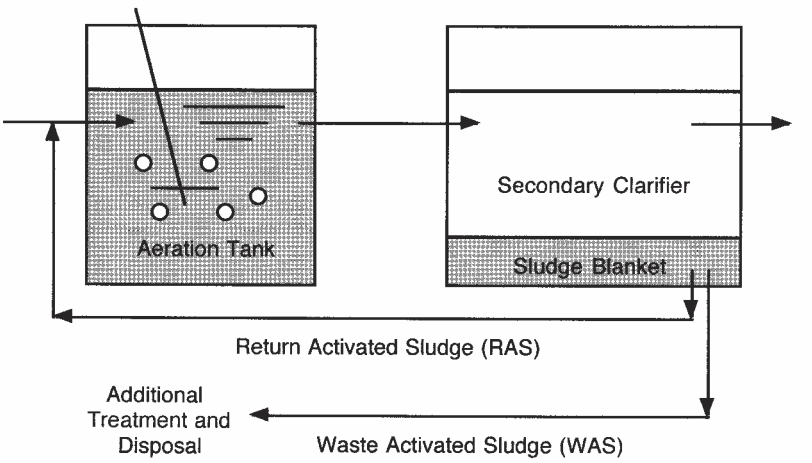

Figure 1.10 *RAS and WAS. Floc particles or activated sludge that is returned to the aeration tank from the secondary clarifier are referred to as return activated sludge (RAS). Floc particles are returned to the aeration tank to treat wastewater. Floc particles or activated sludge that is removed or wasted from the secondary clarifier are referred to as waste activated sludge (WAS). Floc particles are wasted from the activated sludge process because the bacteria are too numerous or too old or have experienced toxicity.*

TABLE 1.5 Common Settleability Problems and Loss of Solids Conditions at Activated Sludge Processes

Undesired filamentous growth
Nutrient-deficient floc particles
Denitrification
Sheared floc particles
Dispersed floc particles
Heavy metals and congealed floc particles
Low dissolved oxygen concentration
Young sludge age
Floc particles lost through sludge aging
Slug discharge of soluble cBOD
Viscous floc or Zoogloeal bulking
Increase in percent MLVSS
Colloidal floc particles
Elevated or depressed temperature
Foam production and accumulation
Scum production and accumulation

or floc particle structure occurs as a result of a significant change in quantity or quality of an industrial discharge or an inappropriate change in the operational condition of the activated sludge process. There are several significant undesired changes in bacterial activity or floc particle structure that often result in settleability problems and loss of solids from the secondary clarifier (Table 1.5).

Undesired changes in the activity of the bacteria may adversely affect floc particle structure, and undesired changes in floc particle structure may adversely affect

bacterial activity. An example of an undesired change in activity of the bacteria that adversely affects floc particle structure is denitrification.

Denitrification in the secondary clarifier results in the production of insoluble molecular nitrogen (N_2) and nitrous oxide (N_2O). As these gases become entrapped in the floc particles or sludge blanket, the sludge blanket becomes buoyant. With increased buoyancy, large clumps of solids rise to the surface of the clarifier and are lost from the activated sludge process. Because of the loss of solids and a poorly compacted sludge blanket, fewer solids (bacteria) are present in the RAS, and a loss of treatment efficiency occurs in the aeration tank. Denitrification in the secondary clarifier is an undesired change in bacterial activity that adversely affects floc particle structure, treatment efficiency, and permit compliance. If chemicals are used to thicken and capture solids in the secondary clarifier, denitrification results in increased operational costs.

An example of an undesired change in floc particle structure that adversely affects bacterial activity is the rapid growth of filamentous organisms. A low dissolved oxygen level, nutrient deficiency, or other stimulatory growth conditions may cause the rapid proliferation of filamentous organisms. This growth results in increased buoyancy of floc particles. Because buoyant floc particles settle poorly in the secondary clarifier, some particles or solids are lost from the activated sludge process. As a result of the loss of solids and a poorly compacted sludge blanket, fewer solids (bacteria) are present in the RAS and a decrease in bacterial activity occurs in the aeration tank. The rapid growth of filamentous organisms in the aeration tank is an undesired change in floc particle structure that adversely affects bacterial activity, treatment efficiency, and permit compliance. If chemicals are used to thicken and capture solids in the secondary clarifier, the rapid growth of filamentous organisms results in increased operational costs.

2

Floc Formation

Three requirements must be satisfied by the bacterial population of an activated sludge process for the process to efficiently degrade BOD and remove fine solids and heavy metals. First, the bacterial population must be large. The larger the population of bacteria, the larger the quantity of BOD that can be degraded and the larger the quantity of fine solids that can be removed. Second, because no one bacterium can degrade all wastes, a great diversity of bacteria is needed. The greater the diversity of bacteria, the larger the variety of wastes that can be degraded. Third, for any bacterial population to efficiently degrade BOD and remove fine solids and heavy metals, the population must be active, that is, no toxic or inhibitory condition can exist in the activated sludge process.

To maintain a large, diverse, and active population of bacteria in the activated sludge process, it is necessary to produce large numbers of firm, dense floc particles, that is, it is critical to ensure proper floc formation. The bacteria in floc particles are the primary organisms responsible for degradation of BOD and removal of fine solids and heavy metals.

By maintaining proper floc formation, bacteria in the RAS may be used over and over to degrade and remove wastes. The floc particles can be recycled without being sheared or strengthened with chemical addition. By maintaining proper floc formation, bacteria in the WAS may be removed without being thickened with chemical addition. Efficient recycling of bacteria and efficient removal of bacteria are achieved through the production of firm, dense, and readily settleable floc particles.

The degradation of wastes refers to the oxidation of cBOD by organotrophic bacteria and the oxidation of nBOD by nitrifying bacteria. When these wastes are oxidized, they are converted to less polluting wastes and nonpolluting wastes and transformed into additional bacterial cells or MLVSS. The removal of wastes refers to the adsorption of fine solids and heavy metals from the bulk solution to the surface of floc particles. These solids are adsorbed to the surface of the floc particles because the surface charge of the solids is compatible for adsorption or the surface charge

of the solids is made compatible for adsorption through the coating action of secretions from ciliated protozoa, rotifers, and free-living nematodes.

Floc formation in the activated sludge process is initiated by a small number of bacteria that are commonly called floc-forming bacteria (Table 2.1). Floc-forming bacteria agglutinate or stick together with increasing sludge age.

Many of the floc-forming bacteria as well as most bacteria that are incorporated in floc particles are Gram-negative, facultative anaerobes. Gram-negative bacteria stain red or pink when exposed to a series of differential stains. Facultative anaerobes are bacteria that can use free molecular oxygen (O_2) or another molecule, for example, nitrate ions (NO_3^-), to degrade cBOD. For these reasons, floc particles in the activated sludge process stain Gram negative and "stick together" in the absence of free molecular oxygen and the presence of nitrate ions.

With increasing sludge age, floc-forming bacteria produce three cellular components that are necessary for floc formation to occur (Figure 2.1). These components

TABLE 2.1 Genera of Floc-Forming Bacteria Commonly Found in Activated Sludge Processes

Achromobacter	*Escherichia*
Aerobacter	*Flavobacterium*
Alcaligens	*Nocardia*
Arzthrobacter	*Sphaerotilus*
Bacillus	*Pseudomonas*
Citromonas	*Zoogloea*

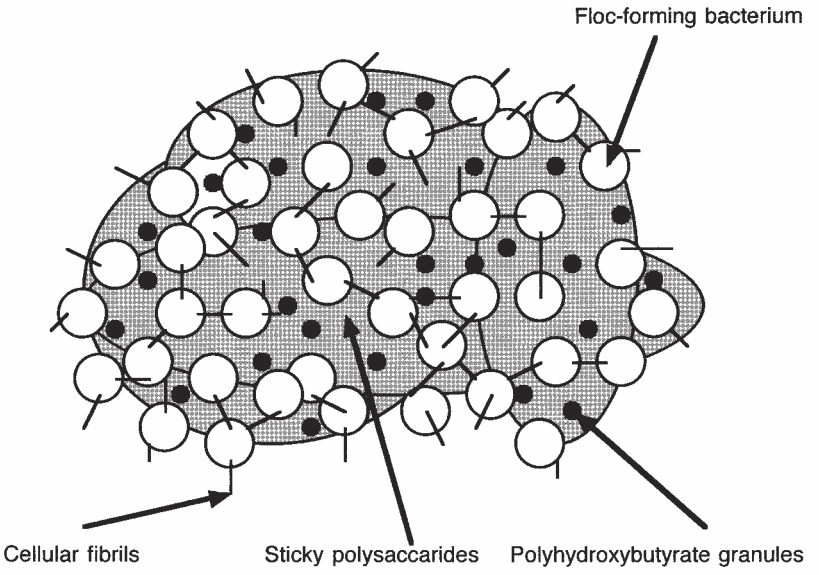

Figure 2.1 *Cellular components necessary for floc formation. Three cellular components are needed for floc formation. These components are produced by floc-forming bacteria with increasing sludge age and consist of cellular fibrils, sticky starches or polysaccharides, and granular starches such as polyhydroxybutyrate. The cellular fibrils connect (bond) one bacterial cell to another bacterial cell. The polysaccharides also bond one bacterial cell to another bacterial cell, whereas the granular starches help to anchor the bacterial cells together.*

are cellular fibrils, sticky starches or polysaccharides, and granular starches, the most important being polyhydroxybutyrate (PHB).

There are several important living and inert components of the floc particle. The major living components consist of three types of bacteria, two groups of protozoa, rotifers, and free-living nematodes. The inert components of the floc particle consist of biological secretions, colloids, heavy metals, and fats, oils, and grease (FOG).

Although algae, fungi, and a variety of other unicellular organisms are incorporated in floc particles, bacteria are the largest group of unicellular organisms in floc particles. Bacteria are present in billions per gram of solids.

There are three types of bacteria with respect to floc particle structure (Figure 2.2). They include floc-forming bacteria, non-floc-forming bacteria, and filamentous organisms. Floc-forming bacteria initiate floc formation, degrade cBOD, and remove fine solids and heavy metals. Non-floc-forming bacteria also degrade cBOD and remove fine solids and heavy metals. Filamentous organisms degrade cBOD, remove

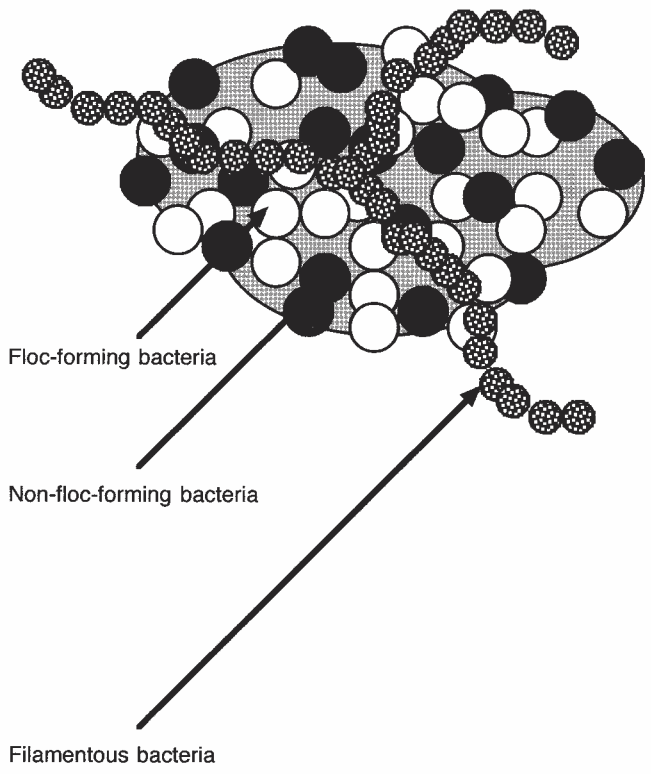

Figure 2.2 *Bacteria involved in floc particle structure. Three types of bacteria are involved in floc formation. The bacteria consist of floc-forming bacteria, non-floc-forming bacteria, and filamentous bacteria. Floc-forming bacteria initiate floc formation through the production of cellular fibrils, sticky polysaccharides, and granular starches. Non-floc-forming bacteria and filamentous bacteria are incorporated in the floc bacteria through compatible charges or adsorption through the activity of ciliated protozoa and metazoa. With increasing sludge age, the filamentous bacteria form chains that extend through the developing floc particle and into the bulk solution. The filamentous chains provide strength to the floc particles, which enables the floc particle to resist shearing action and grow in size.*

fine solids and heavy metals, and provide strength to the floc particle. This strength allows the floc particle to resist shearing action and to increase in size.

Filamentous organisms are excellent degraders of simplistic, soluble cBOD. Some filamentous organisms, such as the Nocardioforms and *Bacillus* spp., are capable of degrading complex wastes. In adequate numbers, filamentous organisms are highly desired for proper floc formation. Filamentous organisms that grow inside the floc particle and extend into the bulk solution from the perimeter of the floc particle provide a network or chain of strength that enables the floc particle to resist shearing action. By resisting shearing action, the floc particle does not break apart, and fine solids are not released. By resisting shearing action, the floc particle grows in size. An increase in size of the floc particle provides a larger number and a greater diversity of bacteria for the treatment of a larger quantity and a larger variety of wastes.

Although the growth of floc-forming bacteria and filamentous organisms is desired and necessary in the activated sludge process, the rapid growth of floc-forming bacteria and filamentous organisms is undesired. This rapid growth results in increased buoyancy of floc particles. Increased buoyancy causes settleability problems and loss of solids.

Because crawling ciliated protozoa are on the floc particle and stalk ciliated protozoa are attached to the floc particle, these two protozoan groups are considered part of the floc particle (Figure 2.3). The protozoa perform several positive roles in the activated sludge process. They add weight to the floc particles and improve solids settleability. They crop bacteria from the bulk solution and release sticky secretions that coat fine solids. Their coating action makes the solids more compatible for adsorption to the surface of floc particles, and they also help to recycle nitrogen and phosphorus by cropping and digesting bacteria and excreting nitrogen-containing and phosphorus-containing wastes to the bulk solution.

Rotifers and free-living nematodes that are on floc particles or burrow into floc

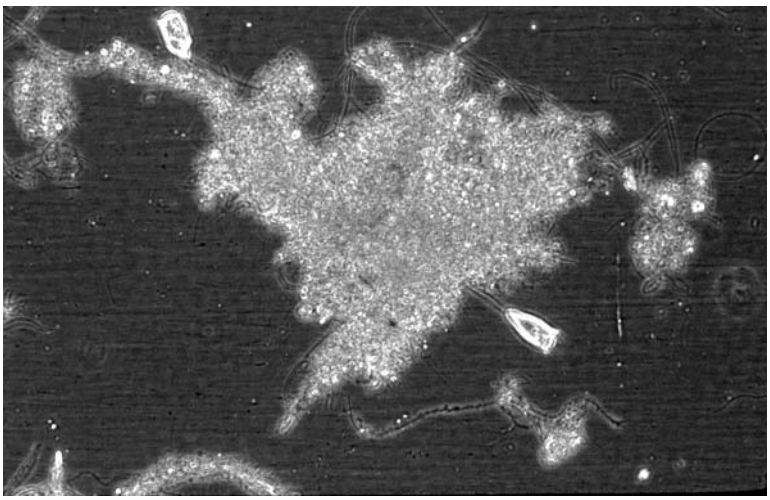

Figure 2.3 *Stalk ciliated protozoa attached to a floc particle. Stalk ciliated protozoa are sessile, that is, they are typically found attached to floc particles. Sessile stalk ciliated protozoa add weight to the floc particle, which contributes to improved settleability of solids.*

particles also are part of the floc particles. They add weight to the floc particles and improve solids settleability. Rotifers and free-living nematodes crop bacteria and release sticky secretions that coat fine solids, making the solids more compatible for adsorption to the surface of the floc particles. They recycle nitrogen and phosphorus by cropping and digesting bacteria and protozoa and excreting nitrogen-containing and phosphorus-containing wastes to the bulk solution. They may package these wastes in small bundles that serve as sites for the development of new floc particles.

Significant inert components of floc particles consist of biological secretions, colloids, heavy metals, and FOG. Biological secretions consist of lipids, gelatinous materials, and proteinaceous materials. These secretions are from bacteria, protozoa, and metazoa. Some of the secretions from filamentous organisms and floc-forming bacteria contribute to foam production by entrapping air bubbles or gases. The capture of air bubbles and gases and the low density of these insoluble secretions contribute to the production of buoyant floc particles.

Many of the colloids that accumulate in floc particles do not degrade or only degrade slowly and consist of proteins that are found in dairy, domestic, and meat processing wastes. Heavy metals in the bulk solution are easily and quickly adsorbed to floc particles. Most heavy metals in the activated sludge process are discharged to the process in industrial wastes. Fats, oils, and grease discharged to the activated sludge process in commercial, domestic, and industrial wastes are adsorbed by floc particles. Some of the fats and oils that are similar in chemical composition to the lipids in the bacterial cell walls are absorbed into the cell walls.

Together, the living and inert components of floc particles undergo floc formation with increasing sludge age, until a mature floc particle is developed. A mature floc particle that has developed without the occurrence of an operational problem or the interruption of floc formation possesses several highly desirable characteristics (Table 2.2). Among the characteristics that are most desirable are strength and density.

Floc formation in the activated sludge process occurs gradually and is strongly influenced by temperature (Table 2.3). With increasing temperature, increasing biological activity occurs and floc formation accelerates.

TABLE 2.2 Characteristics of a Mature Floc Particle

Golden brown in color
Medium (150–500 μm) or large (>500 μm) in size
Irregular in shape
Insignificant accumulation of fats, oils, and grease
No rapid, floc-forming bacterial growth
No undesired filamentous growth
Tightly adjoined, dense bacterial growth

TABLE 2.3 Temperature and the Time Required for Floc Formation

Temperature	Time Required for Floc Formation
<12°C	>4 weeks
≥12°C	2–4 weeks

As floc formation occurs in the activated sludge process, numerous changes occur in the biomass and the bulk solution. These include changes in the size, shape, and strength of the floc particle, the quality of the bulk solution, and the numbers of protozoa, rotifers, and free-living nematodes in the bulk solution and on the floc particle. These changes occur with increasing sludge age and can be illustrated with a floc formation model.

3

A Floc Formation Model

As floc formation occurs in the activated sludge process, numerous changes occur in the biomass and the bulk solution. These changes occur as the floc particles develop from a young sludge age to an old sludge age (Table 3.1). These changes with increasing sludge age can be illustrated by a floc formation model that incorporates the bacterial growth curve (Figure 3.1).

Changes in the number of bacteria and sludge age of the activated sludge process occur as a result of the amount of solids removed from the system (WAS) and the amount of solids lost in the final effluent. Decreased WAS rates provide for a larger concentration of MLVSS and an older sludge age, and increased WAS rates provide for a smaller concentration of MLVSS and a younger sludge age. As the WAS rate is changed, the sludge age of the activated sludge process increases or decreases along the bacterial growth curve. Decreased WAS rates permit solids or bacteria to remain in the activated sludge process for a longer period of time. Therefore, the average age of the bacterial population increases. Increased WAS rates permit solids or bacteria to remain in the activated sludge process for a shorter period of time. Therefore, the average age of the bacterial population decreases.

The bacterial growth curve has four distinct phases that are significant with respect to floc formation. These phases are lag, log, declining log, and endogenous (Table 3.2). These phases can be incorporated into a floc formation model.

LAG PHASE

Starting with lag phase, bacteria enter the activated sludge process in fecal waste and through inflow and infiltration (I/I) as soil and water bacteria. Therefore, the number of bacteria at the beginning of lag phase or start-up of the activated sludge process is not zero.

During lag phase the bacteria in the activated sludge process are active, but

TABLE 3.1 Characteristics of Floc Particles at Young Sludge Age and Old Sludge Age

Characteristic of Floc Particles	Young Sludge Age	Old Sludge Age
Fibril production	Few	Many
Fibril charge	Low	High
Polysaccharide production	High	Low
Polysaccharide strength	Weak	Strong
PHB deposition in floc particles	Core mostly	Core and perimeter
Floc particle size	Small	Medium and large
Floc particle shape	Spherical	Irregular
Filamentous organisms	Absent or few	Many
Floc particle strength	Usually weak	Usually strong
Floc particle settleability	Usually not desirable	Usually desirable
Ciliated protozoa	Few	Many
Dispersed growth	Significant	Insignificant
Particulate materials	Significant	Insignificant
Colloids	Significant	Insignificant
Diversity of bacteria	Small	Large
Diversity of enzymes	Small	Large

they are not reproducing. The bacteria are going through an adjustment period. During the adjustment period, the bacteria are producing the enzymes that are necessary to degrade BOD and synthesize cellular materials that are needed for reproduction.

Because of the young sludge age of the activated sludge process during lag phase, floc-forming bacteria have not aged sufficiently to produce adequate numbers of fibrils and adequate amounts of polysaccharides and PHB granules for floc formation to occur. Also, filamentous organisms have not aged sufficiently to grow from a single cell into a chain of cells.

During lag phase the pollution level or quantity of BOD in the aeration tank is relatively high, and dissolved oxygen concentration is low. Protozoan groups that can survive in large numbers under conditions of high concentrations of BOD and low concentrations of dissolved oxygen are the lowest life forms—amoebae and flagellates (Figure 3.2). During lag phase amoebae and flagellates can compete successfully with the small bacterial population for soluble cBOD. Although ciliated protozoa, rotifers, and free-living nematodes may be found during lag phase, their numbers and activity are greatly reduced. As soil and water organisms, protozoa, rotifers, and free-living nematodes enter the activated sludge process through I/I.

Because of the relatively small bacterial population, degradation of BOD is inefficient. With the absence of floc particles and the presence of a small and sluggish population of ciliated protozoa, rotifers, and free-living nematodes, most fine solids remain suspended in the bulk solution. Therefore, the final effluent of an activated sludge process during lag phase is highly turbid and contains elevated concentrations of BOD and total suspended solids (TSS).

LOG PHASE

During log phase, the bacteria have produced the enzymes necessary to degrade BOD and synthesize cellular materials that are needed for reproduction. Log phase

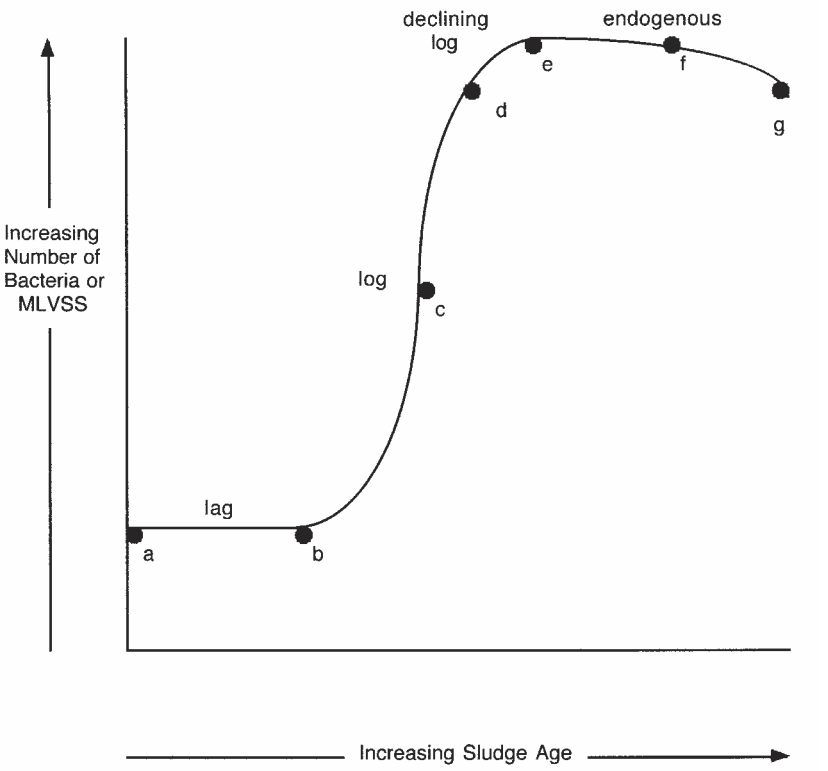

Figure 3.1 *Bacterial growth curve. There are four phases of growth in the bacteria growth curve. These phases are lag, log, declining log, and endogenous. Lag phase starts the bacterial growth curve. During lag phase ("a" to "b"), bacteria are present and active but the bacteria have not yet produced the enzymes that are needed for the degradation of BOD and synthesis of new cellular material. After the necessary enzymes have been produced, the bacteria enter log phase ("b" to "d"). During log phase, soluble BOD is absorbed by the bacterial cells ("b" to "c") and the BOD is degraded and synthesized to cellular material, including new bacterial cells or MLVSS ("c" to "d"). Because the activated sludge process cannot grow more bacteria than the food supply (BOD) permits, the rate of growth of the bacterial population begins to decrease. This decrease in the rate of growth is referred to as declining log phase ("d" to "e"). It is during declining log phase that floc formation begins. Floc-forming bacteria produce cellular fibrils, sticky polysaccharides, and starch granules. With increasing sludge age, endogenous phase of growth occurs ("e" to "g"). During endogenous growth, most of the energy obtained from the degradation of BOD is used for maintaining cellular activity rather than cellular reproduction. Stored food is consumed during endogenous growth. If the bacterial cells exhaust their stored food supply, they may consume their cytoplasm or cellular content. The consumption of cytoplasm is referred to as basal respiration ("f" to "g"). Endogenous phase of growth is associated with a decrease in the number of bacteria.*

can be divided in half. During the first half of log phase, bacterial cells absorb BOD and the volatile content of MLSS increases. The bacteria have not yet reproduced or increased in number. However, this increase in volatile content is considered to be an increase in the number of bacteria on the growth curve because of the increase in the volatile content of the MLSS. During the second half of log phase, cellular synthesis and reproduction have occurred. The bacteria have used the absorbed, soluble cBOD to produce new cells, that is, they have increased in number.

TABLE 3.2 Microbial Condition of the Aeration Tank During Each Phase of the Bacterial Growth Curve

Microbial Condition	Lag Phase	Log Phase	Declining Log Phase	Endogenous Phase
Floc particle	Absent	Absent	Present	Present
Floc particle shape	—	—	Spherical	Irregular
BOD	High	High	Moderate	Low
Dissolved oxygen	Low	Low	Moderate	High
Number of bacteria	Low	Moderate	High	High
Location of most bacteria	Dispersed	Dispersed	Flocculated	Flocculated
Dominant protozoan group	Amoebae and flagellates	Free-swimming ciliates	Crawling ciliates	Crawling ciliates and stalk ciliates
Fine solids	Significant	Significant	Insignificant	Insignificant

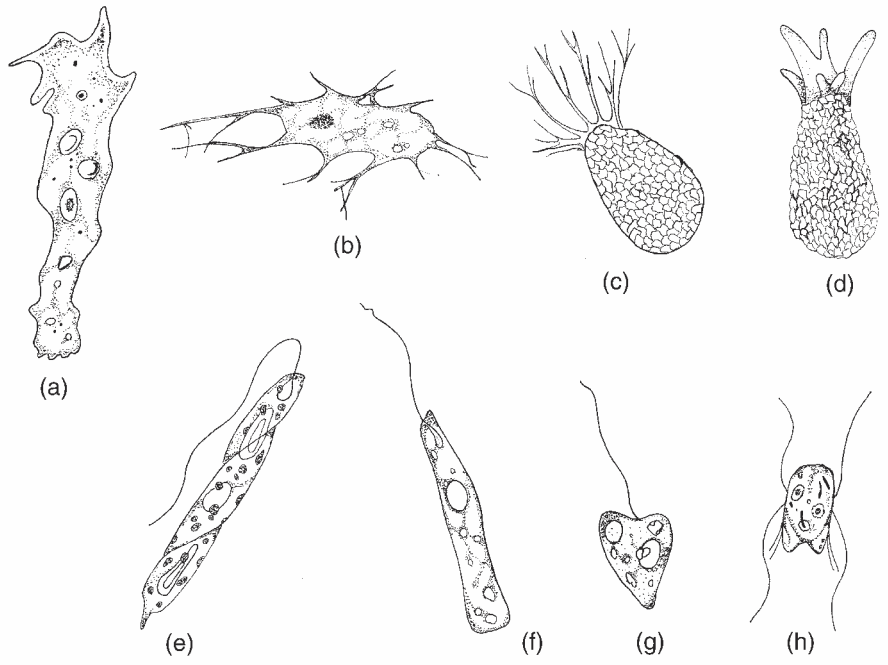

Figure 3.2 *Commonly observed amoebae and flagellates. Commonly observed amoebae in the activated sludge process include* Amoeba *(a) and* Biomyxa *(b), which do not have a protective covering or testate, and* Pseudodifflugia *(c) and* Difflugia *(d), which do have a protective testate. The testate not only provides the amoebae with protection but also permits the amoebae to drift in water currents. Commonly observed flagellates in the activated sludge process include those that are pigmented such as* Euglena *(e) and* Peranema *(f) and those that are nonpigmented such as* Oikomonas *(g) and* Trepomonas *(h). Pigmented flagellates, like algae, contain chloroplasts and are green in color when examined under the microscope. Amoebae and flagellates are usually present as dominant protozoa in the activated sludge process during start-up, toxicity, recovery from toxicity, washout from I/I, and excess sludge wasting.*

Reproduction during log phase is logarithmic or exponential. The growth appears as a constant doubling of the population, for example, 1, 2, 4, 8, 16, 32, 64, 128. . . . Because most organotrophic bacteria have a relatively short generation time of 15–30 minutes, the increase in the number of bacteria during log phase is rapid and significant.

With an increase in the number and diversity of bacteria in the activated sludge process, BOD is rapidly degraded. The degradation of BOD results in less pollution (BOD) and a higher dissolved oxygen concentration.

Free-swimming ciliates increase in number during log phase. Bacteria—their preferred substrate—are plentiful and highly motile in the bulk solution. Free-swimming ciliates have little difficulty finding substrate when bacteria are young, highly motile, and abundant in the bulk solution. With better treatment efficiency, lower pollution level (BOD), higher dissolved oxygen concentration, and abundant substrate (bacteria), free-swimming ciliated protozoa become the dominant protozoan group. The generation time of ciliated protozoa is approximately 24 hours.

Amoebae and flagellates cannot compete effectively for soluble cBOD with an increasing bacterial population and cannot compete effectively for bacteria with ciliated protozoa. Therefore, during log phase the numbers of amoebae and flagellates decrease. Although crawling ciliates, stalked ciliates, rotifers, and free-living nematodes may be found during log phase, their numbers remain relatively small.

With increasing treatment efficiency and the presence of significant cropping action by free-swimming ciliates, the quality of the final effluent improves. BOD and TSS concentrations decrease, and the amount of turbidity also decreases.

DECLINING LOG PHASE

Declining log phase is perhaps the most critical phase of the bacterial growth curve or floc formation model. It is during declining log phase that floc formation begins.

During declining log phase, two important bacterial conditions that are necessary for floc formation are achieved. First, the maximum number of bacteria that can be supported by the quantity of substrate or influent BOD is achieved. Second, the bacteria have been aged sufficiently to produce large numbers of fibrils and large amounts of polysaccharides and PHB granules adequate for floc formation to occur.

When floc formation occurs, the fibrils from different bacteria bond together, insoluble polysaccharides secreted by the bacteria bond together, and PHB granules deposited between bacterial cells help to anchor the cells together. Collectively, fibrils, polysaccharides, and PHB granules initiate floc formation.

Bacterial fibrils originate on the cell membrane and extend through the cell wall into the bulk solution (Figure 3.3). Fibrils are very small in size (2–5 nm) and can only be observed with an electron microscope. Fibrils contain many key chemical groups such as carboxyl (–COOH), hydroxyl (–OH), sulfhydryl (–SOOH), and phosphoryl (–POOH). These chemical groups become ionized in the pH operating range of the activated sludge process. When these chemical groups are ionized, the hydrogen atom is removed from the chemical groups, resulting in the production of the negatively charged chemical groups ($–COO^-$, $–O^-$, $–SOO^-$, and $–POO^-$). Ionization of these chemical groups results in the production of negatively charged fibrils.

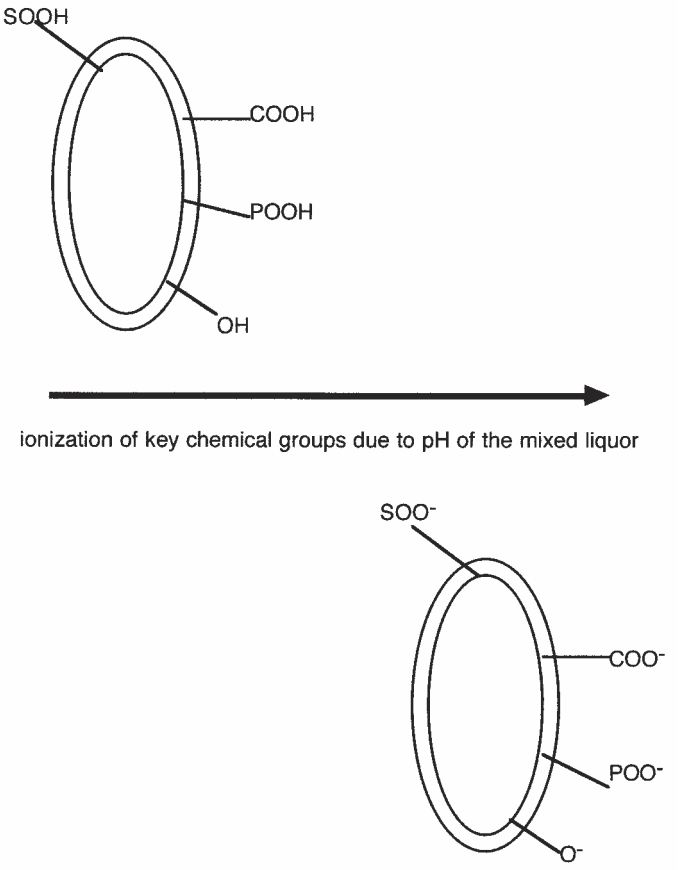

Figure 3.3 *Bacterial fibrils. Bacterial fibrils are 2–5 nm in size and extend from the cell membrane of the bacteria through the cell wall. On each fibril are numerous key functional groups or chemical groups such as sulfhydryl (–SOOH), carboxyl (–COOH), phosphoryl (–POOH), and hydroxyl (–OH). These chemical groups become ionized in the activated sludge process. Ionization occurs when the hydrogen atom (H) is removed from a chemical group. Once ionized, the fibrils and the surface of the bacterial cell become negative or anionic in charge.*

The negatively charged fibrils act as anions that pull or flocculate large numbers of bacteria together when multicharged or multivalent cations such as calcium (Ca^{2+}) bond to the negative sites of fibrils of different bacterial cells. The wastewater entering the activated sludge process is rich in dissolved multivalent cations.

The negative sites on the bacterial fibrils also are known as active sites. The active sites are involved in not only floc formation but also fine solids removal and heavy metal removal (Figure 3.4). Because the pH of the activated sludge process affects the degree of ionization or number of active sites, changes in pH affect floc formation, fine solids removal efficiency, and heavy metal removal efficiency.

Many different insoluble polysaccharides are produced during floc formation. The polysaccharides act as "glues" that help to hold bacterial cells together in a flocculated mass. Some of the polysaccharides are poor binding glues, whereas other polysaccharides are strong binding glues. During declining log phase, copious quan-

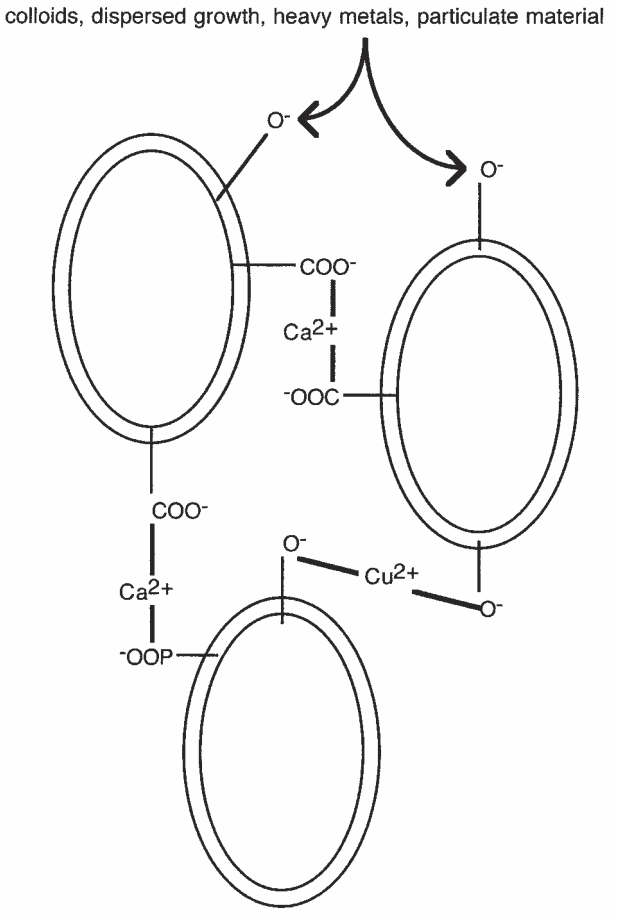

Figure 3.4 *Floc formation and removal of fine solids and heavy metals. When the chemical groups on the bacterial fibrils are ionized, the ionized groups serve as active sites for floc formation, fine solids removal (colloids, dispersed growth, and particulate materials), and heavy metals removal. When soluble bivalent cations such as calcium bond to the active sites of two different bacteria, the bacteria are pulled together or agglutinated. Agglutination is the beginning of floc formation. When fine solids and heavy metals attach to the ionized groups, the fine solids and metals are adsorbed to the surface of the floc particles.*

tities of poor-binding polysaccharides are produced. Therefore, the bacterial cells are held together poorly and far apart.

Insoluble starch granules are produced and deposited between bacterial cells during declining log phase. The most abundant and most important granule is PHB. The starch granules help to anchor the flocculated cells more firmly. However, during declining log phase, the rate of PHB production is much lower than the rate of cellular reproduction. Because of the difference in PHB production and cellular reproduction, PHB granules are found mostly in the core of the floc particles (Figure 3.5). Few PHB granules are found in the perimeter of the floc particles. PHB granules not only anchor bacterial cells together but also anchor particulate materials to the surface of floc. Therefore, the perimeter of the floc particle during declining

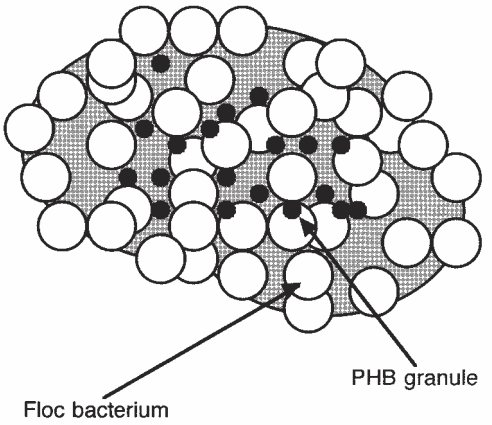

Figure 3.5 *PHB production during declining log phase. When starch granules such as PHB are deposited outside and between floc bacteria, the granules anchor the bacterial cells together. PHB production and deposition in floc particles occurs slowly. During declining log phase PHB granules are produced and deposited, but the rate of production and deposition is much slower than the rate of cellular reproduction. Therefore, PHB are found mostly within the core of the floc particle. The core of the floc particle is firm in the presence of PHB granules, and the perimeter of the floc particle is weak in the absence of PHB granules.*

log phase of growth is buoyant and weak, and particulate material is poorly adsorbed to the surface of the floc particle.

During declining log phase a very large and diverse population of bacteria is present. This population provides for efficient degradation of BOD. The population also serves as an excellent substrate for the growth of a larger and more diverse population of ciliated protozoa. However, the bacteria are becoming less dispersed as floc formation occurs. Because the bacteria are less dispersed, it is difficult for free-swimming ciliated protozoa to find food and they decrease in number. Crawling ciliated protozoa become the dominant protozoan group as they graze on the flocculated masses of bacteria or floc particles.

With increased treatment efficiency, the concentration of BOD decreases in the activated sludge process and the concentration of dissolved oxygen increases. These changes in the activated sludge process promote the proliferation of large numbers of diverse, active ciliated protozoa.

With a large, active population of ciliated protozoa providing cropping and coating action and the presence of many active sites on bacterial fibrils, the bulk solution becomes less turbid as dispersed bacteria are cropped and fine solids are adsorbed to floc particles. During declining log phase, the effluent quality of an activated sludge process improves significantly. Decreases in the concentrations of BOD and TSS occur.

Young floc particles that develop during declining log phase lack filamentous organisms and have difficulty growing in size. The size of young floc particles is limited to the ability of the bacteria to stick together and the amount of shearing action. Therefore, young floc particles usually are small in size (<150 μm) and spherical in shape. Because a small amount of biological secretions and particulate materials are present in the floc particles, young floc particles also are light in color.

ENDOGENOUS PHASE

Endogenous phase of bacterial growth also is known as stationary phase or equilibrium phase. During endogenous phase, little bacterial growth in population size occurs. Most of BOD that is degraded by the bacteria during endogenous phase is used for cellular activity and the maintenance of life rather than cellular synthesis or reproduction.

A significant change in the activated sludge process that occurs during endogenous phase is the growth of filamentous organisms. Sufficient aging has occurred to encourage the growth of filamentous organisms. Once aged, the organisms grow from a single cell into a chain of cells.

Filamentous organisms that were incorporated in the floc particles as single cells during declining log phase begin to grow in length and extend into the bulk solution from the perimeter of the floc particle. Within the floc particle, the filamentous organisms provide the strength that enables the floc particle to resist shearing action. Extended filamentous organisms permit the floc particle to increase in size in the presence of shearing action as floc bacteria grow along the lengths of the filamentous organisms.

Old floc particles that are developed during endogenous phase should have an adequate amount of filamentous organisms to promote the growth of medium (150–500 μm) and large (>500 μm) floc particles. Because the floc bacteria grow along the lengths of the filamentous organisms, the floc particles become irregular in shape. Old floc particles also are dark in color because of the accumulation of large quantities of biological lipids and particulate materials.

Because of the larger and more diverse population of bacteria in the activated sludge process during endogenous phase of growth, improved treatment efficiency occurs. This efficiency provides for the growth of numerous crawling ciliated and stalk ciliated protozoa. The operational conditions for the growth of these protozoa are optimal, that is, pollution level or BOD is relatively low and dissolved oxygen concentration is relatively high. These two protozoan groups compete for dominance. Under optimal conditions protozoa may be present in numbers as high as 50,000 per milliliter.

The large numbers of ciliated protozoa provide for significant cropping action and coating action. The cropping action and coating action remove large quantities of fine solids from the bulk solution. Coating action by ciliated protozoa alone may remove up to one-third of all colloids entering the activated sludge process.

Rotifers, free-living nematodes, other metazoa such as bristleworms, flatworms, and waterbears are strict aerobes and are very sensitive to high pollution levels or BOD. These organisms may be found in relatively large and active numbers during endogenous phase. Because these organisms enter the activated sludge process through I/I, their numbers usually are highly variable. As long as operational conditions are optimal, these organisms should be easily observed.

Rotifers and free-living nematodes have a generation time that is very long compared with those of bacteria and protozoa. The generation time for most rotifers and free-living nematodes is several weeks. This generation time usually is greater than the sludge age of most activated sludge processes.

The long generation time for rotifers and free-living nematodes is one of two significant factors that hinder their increase in numbers. The second factor is the tur-

bulent environment in the activated sludge process that makes it difficult for female and male organisms to meet and copulate.

For most rotifers and free-living nematodes to complete a generation or reproduce, the following life cycle events must occur:

1) A female and a male must find each other and copulate,
2) The female must develop fertile eggs and deposit the eggs in a floc particle,
3) The eggs must hatch, and juveniles must emerge from the eggs, and
4) The juveniles must go through a series of molts to increase in size, mature, and develop sex organs. Usually, several molts are required for maturation of sex organs.

Because of the turbulent environment of the aeration tank and long generation time of rotifers and free-living nematodes, these organisms usually do not reproduce in large numbers in an activated sludge process. Reproduction of these organisms in large numbers may occur, if the process is stable for a relatively long period of time and the process has a very long sludge age. The growth of large populations of these organisms may occur in large aerated lagoons.

Rotifers and free-living nematodes are highly desired in the activated sludge process. These organisms provide cropping action and coating action, add weight to the floc particles, and burrow into the floc particles. The burrowing action permits dissolved oxygen, substrate, and nutrients to penetrate more easily to the core of the floc particle. The burrowing action provides for better treatment efficiency by allowing more bacteria to participate in degrading BOD with adequate dissolved

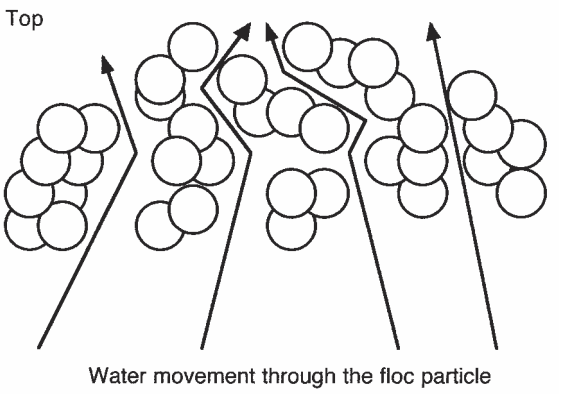

Figure 3.6 *Cross-sectional view of a floc particle. A floc particle is three-dimensional. The particle has length, width, and thickness. A cross-sectional view of the floc particle reveals the presence of openings or channels that are continuous from the bottom to the top of the floc particle. These channels permit the movement of dissolved oxygen, substrate, nutrients, and water through the floc particle. When a floc particle settles in the secondary clarifier, water must move around and through the floc particle. If the channels are plugged with stored food (insoluble cBOD), lipids (foam-producing filamentous organisms), or fats, oils, and grease, water cannot move through the floc particle and its settleability in the secondary clarifier is hindered. If air bubbles or gases become entrapped in the channels, foam production occurs.*

oxygen and nutrients. Also, the insoluble bundles of wastes released by these organisms serve as sites for floc formation.

With increasing sludge age during endogenous phase of growth, the slow-growing nitrifying bacteria *Nitrosomonas* and *Nitrobacter* increase significantly in number. The generation time for nitrifying bacteria is approximately 2–3 days. Under the low pollution level or BOD and high dissolved oxygen concentration in the aeration tank, nitrification occurs.

The floc particle developed during endogenous phase of growth is dark in color, large in size, and irregular in shape. This floc particle, as well as all floc particles, is three-dimensional in structure, that is, it has length, width, and height. The microscope does not reveal the height or thickness of the floc particle.

When a cross-sectional view of a floc particle is examined, numerous openings or channels can be observed (Figure 3.6). The channels permit the flow of dissolved oxygen, substrate, nutrients, and water to the core of the floc particle. The channels also permit the flow of water through the floc particle as it settles in the secondary clarifier.

If the channels become plugged or partially plugged with accumulated materials produced during an undesired operational condition, for example, stored food during a nutrient deficiency or insoluble lipids secreted by foam-producing filamentous organisms, the flow of water through the floc particle is restricted or hindered. As a result of the accumulated materials, desired settling of the floc particle or solids in the secondary clarifier is lost. If air bubbles or gases become entrapped in the channels, foam production occurs.

4

Interruption of Floc Formation

Floc formation in the activated sludge process is dependent on the timely development of adequate numbers of bacterial fibrils, polysaccharides, PHB granules, filamentous organisms, and ciliated protozoa. This development ensures the presence of a large, diverse, and active population of bacteria for acceptable degradation of cBOD and nBOD. The development also ensures the presence of adequate numbers of bacterial fibrils, PHB granules, and ciliated protozoa for the removal of fine solids and heavy metals from the bulk solution.

Floc formation provides for the development of firm, dense, and mature floc particles. These particles are resistant to shearing action and are readily settleable in the secondary clarifier. As the floc particle develops, a balanced growth of filamentous organisms and floc-forming bacteria occurs. Balanced growth is considered to be one to five filamentous organisms extending into the bulk solution from the perimeter of each floc particle. Filamentous organisms may be absent or few in number during a young sludge age, the presence of a complex or difficult-to-degrade cBOD, and the occurrence of toxicity. Filamentous organisms may be present in large and undesired numbers under specific operational or growth stimulatory conditions such as low dissolved oxygen concentration or low pH.

The number of ciliated protozoa that are present in the activated sludge process during floc formation is highly variable. Each process has its own range of numbers of ciliated protozoa during steady-state, operational conditions. Like filamentous organisms, ciliated protozoa may be absent or few in number during specific operational conditions. These conditions include a young sludge age, a low dissolved oxygen level, an undesirable bacterial population, and the occurrence of toxicity.

The interruption of floc formation occurs whenever one of the significant components of floc formation is not properly developed or not developed in adequate numbers or quantities. Whenever this occurs, the development of dense, firm, and mature floc particles is prevented. Several operational conditions are responsible

TABLE 4.1 Operational Conditions Responsible for the Interruption of Floc Formation

Operational Condition	Description or Example
Cell bursting agent	Lauryl sulfate
Colloidal floc	Nondegrading or slowly degrading colloids
Elevated temperature	>32°C
Foam production and accumulation	Foam-producing filamentous organisms
Increase in percent MLVSS	Accumulation of fats, oils, and grease
Lack of ciliated protozoa	<100 per milliliter
Low dissolved oxygen concentration	<1.0 mg/l for 10^+ consecutive hours
Low pH/high pH	<6.5/>8.5
Nutrient deficiency	Usually nitrogen or phosphorus
Salinity	Excessive Na^+ or K^+
Scum production and accumulation	Toxicity and die-off of bacteria
Septicity	ORP of <–150 millivolts
Shearing action (excess turbulence)	Surface aerators
Slug discharge of soluble cBOD	3× soluble cBOD
Surfactant	Anionic detergents
Total dissolved solids (TDS)	>5000 mg/l
Toxicity	Heavy metals, RAS chlorination
Undesired filamentous growth	>5 filamentous organism per floc particle
Viscous floc or Zoogloeal growth	Rapid proliferation of floc-forming bacteria
Young sludge age	<3 days

for the interruption of floc formation that results in the development of weak and buoyant floc particles (Table 4.1).

Although activated sludge processes are designed to operate at a steady-state condition with respect to hydraulic loading and organic loading, most processes experience significant fluctuations in strength and composition of the waste stream. These fluctuations, industrial wastes, changes in operational conditions, equipment problems, and improper design and equipment selection are responsible for undesired changes in activity or structure of the floc particle that produce settleability problems and loss of solids.

Many operational conditions are responsible for the interruption of floc formation. Of these conditions, four occur more commonly in industrial activated sludge processes than in municipal activated sludge processes. These operational conditions are low pH, high pH, salinity, and TDS. These four plus septicity reviewed in this chapter. The remaining operational conditions may occur in either industrial or municipal activated sludge processes and are reviewed in individual chapters.

pH

Low pH and high pH adversely affect floc formation. Proper floc formation occurs within the pH range of 6.5 to 8.5. At pH values below 6.5 and above 8.5, fibril charge and, consequently, floc formation deteriorates. Floc particles become weak and buoyant as bacterial cells pull less tightly together.

Low pH and high pH occur with the discharge of acidic wastes or alkali wastes, respectively. Low pH also may occur as a result of nitrification. Nitrification destroys alkalinity.

Acidic wastes and alkali wastes that interrupt floc formation should be identified, and the wastes should be neutralized. The pH of the aeration tank may be continuously monitored and the pH of the aeration tank adjusted as needed with an appropriate acidic or alkali compound to maintain the pH within a desired range, for example, 6.8–7.2. If nitrification occurs in the activated sludge process, alkali should be added to the aeration tanks.

SALINITY AND TOTAL DISSOLVED SOLIDS (TDS)

Salinity refers to the concentrations of two ions in the bulk solution of the aeration tank. These ions are sodium (Na^+) and potassium (K^+). These ions influence the movement of water in and out of the bacterial cell. The movement of water affects the integrity of the cell membrane, the number and charge of the active sites on the fibrils, and, consequently, floc formation. Like salinity, total dissolved solids (TDS) affects the integrity of the cell membrane, the number and charge of active sites on the fibrils, and, consequently, floc formation.

Bacteria in the activated sludge process can acclimate slowly to small increases in salinity. Although bacteria can acclimate to increases in salinity, they have much difficulty acclimating to decreases in salinity.

An example of the ability of bacteria to acclimate to an increase in salinity would be the increase in salt concentration caused by the discharge of pickle processing wastes. An example of the difficulty of bacteria to acclimate to a decrease in salinity would be the sudden decrease in salinity caused by I/I to an already acclimated process.

SEPTICITY

Septicity occurs in wastewater when the oxidation-reduction potential (ORP) is <–150 mV (Table 4.2). At an ORP value <–150 mV, sulfide (HS^-) may be biologically produced as well as a large variety of simplistic, soluble acids and alcohols. Septicity may occur in dead-end mains, minimum-grade sewers, lift stations, headworks of the treatment process, secondary clarifiers, and thickeners. Septicity does occur in anaerobic digesters. Also, acids and alcohols that are associated with septic conditions may be discharged by industries or industrial pretreatment systems to the sewer system, for example, pickle processing and juice processing wastewater.

The ORP of wastewater is a measurement of the net charge of oxidized compounds and reduced compounds in solution. Nitrate ions (NO_3^-) and sulfate ions

TABLE 4.2 Oxidation-Reduction Potential (ORP) and Septicity

ORP (mV)	Molecule Used to Degrade Soluble cBOD	Production of Sulfide or Simplistic, Soluble cBOD
≥+150	Free molecular oxygen	No
+150 to –150	Nitrite ion or nitrate ion	No
≤–150	Sulfate or soluble cBOD	Yes

(SO_4^{2-}) are examples of oxidized compounds. Ammonium ions (NH_4^+) ions are examples of reduced compounds.

Septicity interferes with bacterial fibril charge, and therefore the interruption of floc formation occurs. With decreasing ORP or increasing septicity, floc formation is more severely affected.

An additional concern related to the occurrence of septicity or the presence of a large variety of simplistic, soluble acids and alcohols is the undesired growth of filamentous organisms. Concentrations of sulfides of 3 mg/l or more and of simplistic, soluble acids and alcohols of 200 mg/l or more may trigger the proliferation of filamentous organisms such as *Beggiatoa* sp., *Microthrix parvicella*, *Thiothrix* sp., and type 021N.

Part II

Settleability Problems and Loss of Solids

5

Introduction

Settleability problems and loss of solids at activated sludge processes may be due to one operational condition, such as the undesired growth of filamentous organisms, or several operational conditions, for example, the undesired growth of filamentous organisms and the presence of nutrient-deficient floc particles and foam. Some operational conditions occur frequently at many activated sludge processes and receive much review in the literature. These frequently occurring operational conditions include undesired growth of filamentous organisms, nutrient-deficient floc particles, and denitrification. Several operational conditions occur infrequently at activated sludge processes and receive little review in the literature. Examples of these conditions include cell bursting agents, elevated temperatures, and colloidal floc particles.

To identify the operational conditions responsible for settleability problems and loss of solids in the activated sludge process, the checklist of indicators in Tables 5.1–5.15 may be used. As more and more indicators are checked for each operational condition responsible for settleability problems and loss of solids, the condition is more likely to occur in the activated sludge process. Each operational

TABLE 5.1 Indicators of Operational Conditions Responsible for Undesired Filamentous Growth

X if applicable	Indicator
	Many filamentous organisms growing in the floc particles
	Many short filamentous organisms extending into the bulk solution
	Many translucent filamentous organisms
	Presence of significant interfloc bridging
	Presence of significant open floc formation
	Relative abundance rating for filamentous organisms at “4,” “5,” or “6”

TABLE 5.2 Indicators of Operational Conditions Responsible for Nutrient-Deficient Floc Particles

X if applicable	Indicator
	Billowy white foam at a young sludge age
	Greasy gray foam at an old sludge age
	Positive India ink reverse stain
	Significant growth of nutrient-deficient filamentous organisms
	Target values for nitrogen and phosphorus not satisfied in mixed liquor effluent filtrate during peak loading conditions

TABLE 5.3 Indicators of Operational Conditions Responsible for Denitrification

X if applicable	Indicator
	Decrease in NO_3^- concentration across the secondary clarifier
	Increase in alkalinity or pH across the secondary clarifier
	Large clumps of dark solids rising in the secondary clarifier
	Numerous bubbles rising in the secondary clarifier
	Reduction in NO_2^- and NO_3^- across the secondary clarifier
	Reduction in redox potential across the secondary clarifier

TABLE 5.4 Indicators of Operational Conditions Responsible for Sheared Floc Particles

X if applicable	Indicator
	Numerous sheared stalk ciliated protozoa
	Significant or excessive amount of dispersed growth
	Small (<150 μm), irregularly shaped floc particles dominate

TABLE 5.5 Indicators of Operational Conditions Responsible for Dispersed Floc Particles

X if applicable	Indicator
	Dispersed metazoa
	Significant or excessive amount of dispersed growth
	Sluggish activity or inactivity of protozoa and metazoa
	Small (<150 μm), spherically shaped floc particles dominate

TABLE 5.6 Indicators of Operational Conditions Responsible for Heavy Metals and Congealed Floc Particles

X if applicable	Indicator
	Build-up of NO_2^- in mixed liquor effluent
	Dense, oval-shaped floc particles
	Higher than expected concentrations of target values for nitrogen and phosphorusin mixed liquor effluent filtrate during peak loading conditions
	Regression of dominant protozoan groups to amoebae and flagellates
	Significant or excessive amount of dispersed growth
	Sluggish activity or inactivity of protozoa and metazoa

TABLE 5.7 Indicators of Operational Conditions Responsible for Low Dissolved Oxygen Concentration

X if applicable	Indicator
	Significant growth of low-dissolved-oxygen filamentous organisms
	Numerous free-swimming, stalk ciliated protozoa
	Regression of dominant protozoan groups to amoebae and flagellates
	Significant or excessive amount of dispersed growth
	Sluggish activity or inactivity of protozoa and metazoa
	Weak methylene blue-staining floc particles dominate

TABLE 5.8 Indicators of Operational Conditions Responsible for Young Sludge Age

X if applicable	Indicator
	Amoebae and flagellates dominate
	Billowy white foam
	Significant or excessive amount of dispersed growth
	Weak methylene blue-staining floc particles dominate

TABLE 5.9 Indicators of Operational Conditions Responsible for Floc Particles Lost Through Sludge Aging

X if applicable	Indicator
	Ashing occurs
	Clumping occurs (see denitrification)
	Pinpoint floc or pin floc dominates
	Straggler floc dominates

TABLE 5.10 Indicators of Operational Conditions Responsible for Slug Discharge of Soluble cBOD

X if applicable	Indicator
	Floc particles with firm core and weak perimeter dominate
	Significant or excessive amount of dispersed growth

TABLE 5.11 Indicators of Operational Conditions Responsible for Viscous Floc or Zoogloeal Growth

X if applicable	Indicator
	Billowy white foam
	Significant amount of amorphous Zoogloeal growth
	Significant amount of fingerlike Zoogloeal growth

TABLE 5.12 Indicators of Operational Conditions Responsible for Increase in MLVSS

X if applicable	Indicator
	Significant increase in percent MLVSS
	Weak methylene blue-staining floc particles dominate

TABLE 5.13 Indicators of Operational Conditions Responsible for Colloidal Floc Particles

X if applicable	Indicator
	Weak methylene blue-staining floc particles dominate

TABLE 5.14 Indicators of Operational Conditions Responsible for Elevated or Depressed Temperature

X if applicable	Indicator
	Decreased numbers of protozoa and metazoa
	Sluggish activity or inactivity of protozoa and metazoa
	Weak methylene blue-staining floc particles dominate

TABLE 5.15 Indicators of Operational Conditions Responsible for Production and Accumulation of Foam and Scum

X if applicable	Indicator
	Billowy white foam occurring with increase in alkalinity
	Billowy white foam occurring with nutrient deficiency (young sludge)
	Billowy white foam occurring with overdose of cationic polymer
	Billowy white foam occurring with viscous floc or Zoogloeal growth
	Greasy gray foam occurring with nutrient deficiency (old sludge)
	Surfactant foam occurring in the presence of toxicity
	Surfactant foam occurring with relatively low MLVSS
	Surfactant foam occurring with slug discharge of soaps or detergents
	Viscous chocolate-brown foam with foam-producing filaments
	Viscous dark brown or black foam in presence of excess FOG

condition responsible for settleability problems and loss of solids is reviewed in its own chapter. Detailed information on the causes, identification, and control of each operational condition are provided.

6

Undesired Filamentous Growth

Filamentous organisms are chains of microscopic cells. There are approximately 30 filamentous organisms that are commonly found in activated sludge processes. Most filamentous organisms are usually 50–1000 µm in length and are straight, curved, or coiled in shape. Filamentous organisms may be found within the floc particles, extending into the bulk solution from the perimeter of floc particles, and free-floating in the bulk solution.

Filamentous organisms enter activated sludge processes in relatively large numbers as individual cells, short chains of cells, or broken chains from a variety of sources. Filamentous organisms are common soil and water organisms that enter an activated sludge process through I/I. They grow in the biomass covering the bottom of manholes and the inside of sewer mains and are continuously washed into activated sludge processes as wastewater flows over the biomass. Industries that use biological processes to pretreat their wastewater before it is discharged to a municipal sewer system may discharge filamentous organisms in their effluent.

Three groups of filamentous organisms affect the operation of an activated sludge process. These organisms are algae, bacteria, and fungi. Most filamentous organisms are bacteria. The bacterial group includes the Nocardioforms that are best known for their production of viscous, chocolate-brown foam on the surface on an aeration tanks and collapsed foam (scum) on the surface of secondary clarifiers (Figures 6.1 and 6.2). Examples of Nocardioforms include *Nocardia amarae* and *Nocardia pinensis*.

Algae, bacteria, and fungi make up the filamentous organisms that commonly are found in activated sludge processes (Table 6.1). These organisms may be identified by genus name such as *Thiothrix*, binome (genus and species name), for example, *Sphaerotilus natans*, or type number (type 1701). A genus is a collection of individual organisms (species) that share many, but not all, characteristics.

The binome of an organism is either italicized or underlined. The first letter of the genus name is always capitalized. If the species name is not known or provided,

Figure 6.1 *Nocardial foam on the surface of an aeration tank. Filamentous organism foam such as that produced by Nocardioforms is typically viscous and chocolate-brown. Active and dead cells produce the foam. Active cells release lipids that coat the floc particles and capture air bubbles and gases, and dead cells release biosurfactants that reduce the surface tension of the wastewater. The major biosurfactants released are ammonium ions and fatty acids.*

Figure 6.2 *Collapsed Nocardial foam or scum on the surface of a secondary clarifier. When filamentous organism foam enters the secondary clarifier, entrapped air bubbles and gases are released as the foam spills over the influent weirs of the clarifier. The escape of air bubbles and gases causes the foam to collapse. The collapsed foam often is referred to as scum.*

"sp." is used to indicate one species of the genus; "spp." is used to indicate two or more species of the genus.

Some filamentous organisms grow differently in the activated sludge process than they do in pure cultures in a laboratory under controlled conditions. Therefore, these

TABLE 6.1 Significant Filamentous Organisms Commonly Found in the Activated Sludge Process

Bacillus spp.	Type 0041
Beggiatoa spp.	Type 0092
Cyanophyceae	Type 0211
Flexibacter spp.	Type 0411
Fungi	Type 0581
Haliscomenobacter hydrossis	Type 0675
Herpetosiphon spp.	Type 0803
Microthrix parvicella	Type 0914
Nocardioforms	Type 0961
Nostocoida limicola	Type 1701
Sphaerotilus natans	Type 1702
Streptococcus spp.	Type 1851
Thiothrix spp.	Type 1852
Trichococcus spp.	Type 1863
Type 021N	

filamentous organisms are difficult to identify with a genus or binome and are given a type number, for example, type 1701.

The composition of wastewater that is being treated and the operational conditions that exist during treatment determine what and how many filamentous organisms grow in an activated sludge process. Most municipal activated sludge processes usually have three to five significant filamentous organisms. Industrial activated sludge processes may have only one or two significant filamentous organisms, if the wastes (cBOD) are complex in chemical structure and degrade slowly. Industrial activated sludge processes that treat simplistic wastes (cBOD) that are degraded easily may have eight or more significant filamentous organisms.

Filamentous organisms grow in activated sludge processes, and their presence is desired in adequate numbers. When present in adequate numbers, filamentous organisms perform two beneficial roles. They degrade soluble cBOD, and they provide strength for floc formation.

Because filamentous organisms grow in floc particles and extend into the bulk solution from the perimeter of the floc particles, they give strength to the floc particles. This strength permits floc particles to increase in size in the presence of excess turbulence. Thus fewer solids are lost through shearing action, and a large and diverse bacterial population is maintained in the activated sludge process.

The relative abundance of filamentous organisms within an activated sludge process may be rated on a scale of "0" to "6" with "0" being "none" and "6" being "excessive" (Table 6.2). An adequate number of filamentous organisms in activated sludge process is rated as "3" or "common." At this rating one to five filamentous organisms extend into the bulk solution from the perimeter of most floc particles.

At ratings less than "3" or "common," an inadequate number of filamentous organisms are present. The lack of filamentous growth is usually caused by a young sludge age, complex wastes (cBOD), or toxicity.

Many filamentous organisms, such as type 0092 and type 1851, increase in number simply by aging. Therefore, a young sludge tends to grow a smaller number of filamentous organisms than an old sludge. Because most filamentous organisms

TABLE 6.2 Relative Abundance Ratings for the Growth of Filamentous Organisms (after Jenkins et al., 1993)

Relative Abundance Rating	Term	Description	Adverse Impact on Settleability Expected
0	"None"	Filamentous organisms not observed	"NO"
1	"Insignificant"	Filamentous organisms present, but found in an occasional floc particle in very few fields of view	"NO"
2	"Some"	Filamentous organisms present, but found only in some floc particles	"NO"
3	"Common"	Filamentous organisms observed in most floc particles at low density (1–5 filamentous organisms per floc particle)	"NO" unless significant interfloc bridging or open floc formation occur, or significant growth of foam-producing filamentous organisms in the floc particles
4	"Very common"	Filamentous organisms observed in most floc particles at medium density (6–20 filamentous organism per floc particle)	"YES"
5	"Abundant"	Filamentous organisms observed in most floc particles at high density (>20 filamentous organisms per floc particle)	"YES"
6	"Excessive"	Filamentous organisms observed in most floc particles; filamentous organisms more abundant than floc particles; or filamentous organisms growing in large numbers in the bulk solution	"YES"

degrade simplistic soluble cBOD, the presence of complex wastes does not provide a suitable substrate for the growth of many filamentous organisms. Complex wastes are associated with industrial wastewaters. Because filamentous organisms have more surface area exposed to the bulk solution than floc bacteria, filamentous organisms are more harshly affected and grow more slowly than floc bacteria. An example of the effect of toxicity on filamentous organisms can be observed when the RAS is chlorinated to control the undesired growth of filamentous organisms.

If filamentous organisms are not present or are present only in small numbers, their growth may be encouraged through several changes in operational conditions. If possible, the sludge age may be increased to age the existing population of filamentous organisms. The substrate within the activated sludge process can be augmented with a food source (cBOD) more compatible with the growth of filamentous organisms. Chicken feed, dog food, and rabbit food can be added to the activated sludge process to encourage the growth of filamentous organisms. Also, bioaugmentation products can be added to the activated sludge process to degrade complex wastes to simplistic soluble wastes that are compatible with the growth of filamentous organisms. Finally, toxic wastes that inhibit the growth of filamentous

TABLE 6.3 Operational Conditions Associated with the Rapid Growth of Filamentous Organisms

Operational Condition	Filamentous Organism
High MCRT (>10 days)	0041, 0092, 0581, 0675, 0803, 0961, 1851, *M. parvicella*
Fats, oils, and grease	0092, *M. parvicella*, Nocardioforms
High pH (>8.0)	*Microthrix parvicella*
Low dissolved oxygen and High MCRT	*M. parvicella*
Low dissolved oxygen and low to moderate MCRT	1701, *H. hydrossis*, *S. natans*
Low F/M (<0.05)	021N, 0041, 0092, 0581, 0675, 0803, 0961, *H. hydrossis*, *M. parvicella*, Nocardioforms
Low nitrogen or phosphorus	021N, 0041, 0675, 1701, *H. hydrossis*, Fungi, Nocardioforms, *S. natans*, *Thiothrix* spp.
Low pH (<6.5)	Fungi, Nocardioforms
Organic acids	021N, *Beggiatoa* spp., *Thiothrix* spp.
Readily biodegradable substrates (alcohols, amino acids with sulfur, glucose, volatile fatty acids)	021N, 1851, *H. hydrossis*, Nocardioforms, *N. limicola, S. natans*, *Thiothrix* spp.
Septicity/sulfides (1–15 mg/l)	021N, 0041, *Beggiatoa* spp., *N. limicola*, *Thiothrix* spp.
Slow biodegradable substrates	0041, 0092, 0675, *M. parvicella*, Nocardioforms
Warm wastewater temperature	1701, *S. natans*
Winter proliferation	*M. parvicella*

organisms should be identified and removed from the waste stream or reduced to a safe concentration in the waste stream.

When filamentous organisms increase to a rating greater than "3," settleability problems and loss of solids usually occur. This is because of the buoyant nature of the floc particles produced through the growth of undesired numbers of filamentous organisms or the accumulation of lipids that are secreted by any foam-producing filamentous organism. This growth is the result of a change in the strength or character of the waste stream, usually industrial, or operational condition.

Several operational conditions contribute to the undesired growth of filamentous organisms. These conditions include cold temperature, low dissolved oxygen concentration, low food-to-microorganism ratio or F/M (Appendix I), nutrient deficiency for nitrogen or phosphorus, presence of excess FOG, presence of septicity or sulfides, low pH, high pH, and high sludge age or MCRT. Each condition can be related to the undesired growth of specific filamentous organisms (Table 6.3).

In addition to the undesired growth of filamentous organisms that contribute to settleability problems and loss of solids, significant amounts of interfloc bridging or open floc formation also contribute to solids settleability problems and loss of solids. Interfloc bridging is the joining or bridging in the bulk solution of the extended filamentous organisms from the perimeter of two or more floc particles (Figure 6.3). Open floc formation is the scattering of the floc bacteria in many small groups along the lengths of the filamentous organisms within the floc particles (Figure 6.4). Open floc formation also is known as diffused floc formation.

To determine whether filamentous organisms are responsible for settleability problems or loss of solids, microscopic analyses of a sample of mixed liquor should be performed. A wet mount of a stirred mixed liquor effluent sample of an in-line

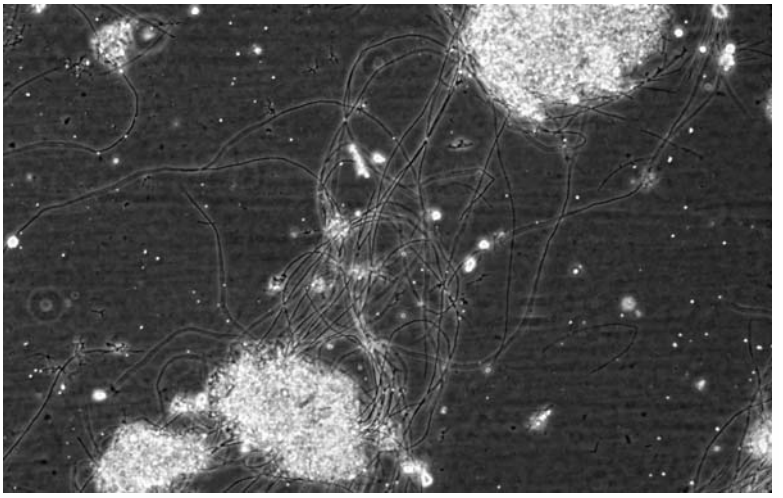

Figure 6.3 *Interfloc bridging. Interfloc bridging is the joining in the bulk solution of the extended filamentous organisms from the perimeter of two or more floc particles. Interfloc bridging adversely affects solids settleability in the secondary clarifier.*

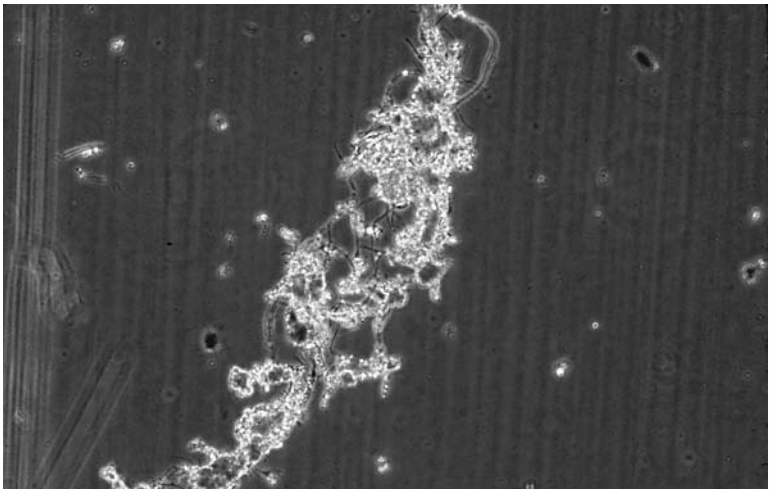

Figure 6.4 *Open floc formation. Open floc formation is the scattering of the floc bacteria along the lengths of the filamentous organisms within the floc particle. Open floc formation adversely affects solids settleability in the secondary clarifier.*

aeration tank should be scanned under low-power magnification (Appendix II). The microscopic scan should reveal the following information:

- The relative abundance of the filamentous organisms on a scale of "0" to "6," and
- The absence or presence of significant interfloc bridging or significant open floc formation.

At a relative abundance rating greater than "3," the filamentous organisms adversely affect solids settleability and contribute to loss of solids. At a relative abundance rating of "3," the filamentous organisms may adversely affect solids settleability and contribute to loss of solids, if significant interfloc bridging or significant open floc formation is present or there is significant growth of foam-producing filamentous organisms in the floc particle. However, care should be taken not to overlook some filamentous organisms that are translucent or short in length or that grow mostly in floc particles.

Filamentous organisms that may be overlooked include translucent filaments such as type 0092; short filaments, for example *Haliscomenobacter hydrossis* and *Thiothrix* II; and filaments that often grow mostly within floc particles such as *Microthrix parvicella* and some Nocardioforms. Translucent filamentous organisms may be overlooked if too much light intensity is used during a microscopic examination (Appendix II). Short filamentous organisms may be overlooked if the operator is not familiar with short filaments or the operator scans too quickly. Filamentous organisms that grow mostly in floc particles are covered by floc bacteria and may be difficult to observe.

Until the operator becomes familiar with the filamentous organisms that grow in the activated sludge process, the following microscopic techniques should be performed to ensure that filamentous organisms are not overlooked (Appendix II):

- Prepare two smears of the stirred, mixed liquor sample,
- Perform a Gram stain on one smear,
- Perform a Neisser stain on the other smear, and
- Observe each smear under oil-immersion magnification.

Translucent filamentous organisms are easily observed after staining. Under the Gram stain, the filamentous organisms are either pink-red (negative) or blue-violet (positive). Under the Neisser stain, the filamentous organisms are either yellow-brown (negative) or blue-gray (positive). Short filamentous organisms not only stain but also protrude further from the perimeter of the floc particle as the floc bacteria pull together more tightly under the Gram stain and the Neisser stain. Filamentous organisms that grow within the floc particle are more easily observed because they stain differently than the floc bacteria that surround them.

Operational conditions associated with the rapid growth of filamentous organisms in the activated sludge process can be determined by identifying the filamentous organisms. Morphologic or structural features and staining characteristics are used to identify filamentous organism. There are several texts that can be used to identify filamentous organisms (Table 6.4).

CONTROL

A number of operational measures may be used to control undesired filamentous growth (Table 6.5). However, adequate filamentous growth should be maintained in the activated sludge process to obtain the benefits of degradation of soluble cBOD and floc particle strength.

TABLE 6.4 Texts Available for the Identification of Filamentous Organisms

Eikelboom, D. H. and van Buijsen, H. J. J. 1989. Microscopic Sludge Investigation Manual. TNO Research Institute for Environmental Hygiene, Water and Soil Division, P.O. Box 214, 2600 AE Delft, The Netherlands.
Gray, N. F. 1990. Activated Sludge; Theory and Practice. Oxford University Press, New York.
Jenkins, D., Richards, M. G., and Daigger, G. T. 1993. Manual on the Causes and Control of Activated Sludge Bulking and Foaming, 2nd Edition. CRC Lewis Publications. Boca Raton, FL.
Schuyler, R. G., Chairman. 2002. Wastewater Biology: The Microlife, 2nd Edition. Water Environment Federation. Alexandria, VA.

TABLE 6.5 Operational Measures Available for the Control of Undesired Filamentous Growth

Type of Operational Measure	Measures Available
Rapid nonspecific	Increase RAS rate
	Change feed points of RAS and mixed liquor influent to decrease secondary clarifier loading
	Addition of cationic polymers
	Addition of metal salts or coagulants
	Addition of a toxicant, for example, chlorine or hydrogen peroxide
Slow specific	Identify filamentous organism, identify causative factors for growth of filamentous organism, and correct filamentous growth and causative factors
Selectors	F/M
	Anoxic
	Anaerobic
	Feast-and-famine

Rapid, nonspecific control measures for the undesired growth of filamentous organisms are those measures that are used to obtain immediate improvement in solids settleability and reduction in loss of solids without the identification of the responsible filamentous organisms or their operational growth factors. Increasing the RAS rate removes the solids from the secondary clarifier before they are lost from the clarifier. Changing the feed point of the RAS or mixed liquor influent to the aeration tank to reduce solids loading to the secondary clarifier helps to improve solids settleability in the secondary clarifier and to prevent the loss of solids.

The addition of cationic polymers, such as polyacrylamides, and metals salts or coagulants to the mixed liquor effluent or secondary clarifier influent helps to improve solids settleability and reduce the amount of solids that are lost from the secondary clarifier. Coagulants commonly used to overcome the adverse effects of undesired filamentous organisms include alum or aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$), ferric chloride ($FeCl_3$), ferrous sulfate ($FeSO_4 \cdot 7H_2O$), and lime ($Ca(OH)_2$). Polymers and coagulants capture solids, reduce the surface area of extended filamentous organisms, improve the density of floc particles, and add weight to the floc particles.

The use of a toxicant, such as chlorine (Cl_2) in the form of hypochlorous acid (HOCl) or hydrogen peroxide (H_2O_2), to destroy filamentous organisms is very effective in reducing the number of filamentous organisms. Toxicants attack the sheath, cell membrane, and enzymes of the filamentous cells.

Slow, specific control measures for the undesired growth of filamentous organisms are those measures that identify the filamentous organisms and their operational growth factors that are responsible for settleability problems and loss of solids. Besides reducing the filamentous organisms to a manageable number through an appropriate control measure, the operational factors that are responsible for rapid growth of the filamentous organisms are identified and corrected, for example, low pH is increased, high pH is decreased, and urea (H_2NCONH_2) is added for a nitrogen deficiency.

Selectors are tanks, zones within tanks, or time periods in tanks that have operational conditions that favor the growth of floc-forming bacteria over the growth of filamentous organisms. Selectors may have an anaerobic environment or an anoxic environment of 1–2 hours. F/M selectors have high-energy mixing of RAS and influent wastewater for short periods of time (5–15 minutes) to ensure that adequate food penetrates the core of the floc particles. Feast-and-famine selectors provide copious quantities of dissolved oxygen or food for a period of time and then no dissolved oxygen or food for a period of time.

7

Nutrient-Deficient Floc Particles

A nutrient deficiency in an activated sludge process may result in several operational problems (Table 7.1). These problems include loss of settleability, loss of solids, and the production and accumulation of foam.

The nutrient deficiency usually is for nitrogen or phosphorus and most often is associated with the discharge of industrial wastes that are rich in soluble cBOD but lacking in proper quantity and quality of at least one nutrient (Table 7.2). Because industrial wastes are usually responsible for a nutrient deficiency in an activated sludge process, the occurrence of a nutrient deficiency may be examined with respect to the type of wastewater that is treated and the type of nutrient that may be deficient (Table 7.3).

Three types of wastewaters are treated by activated sludge processes. These wastewaters are domestic, industrial, and municipal (Figure 7.1). Domestic wastewater contains relatively large quantities of major and minor nutrients. Although much cBOD is associated with domestic wastewater, much of the cBOD is in the particulate and colloidal forms. These forms of cBOD either do not degrade or only degrade slowly in the activated sludge process. Therefore, they do not place a large and immediate demand for nutrients on the activated sludge process. With relatively large quantities of major and minor nutrients and a relatively small quantity of soluble cBOD, a nutrient deficiency in an activated sludge process that treats only domestic wastewater is unusual. However, a deficiency may occur for phosphorus if the pH of the aeration tank increases above 7.4.

A deficiency for phosphorus may occur when orthophosphate (HPO_4^{2-})—the soluble form of the phosphorus nutrient preferred by bacteria—is made insoluble. Orthophosphate is made insoluble when it combines with a trivalent cation such as aluminum (Al^{3+}) or iron (Fe^{3+}) under a pH value greater than 7.4. In the presence of metal salts such as alum [$Al_2(SO_4)_3 \cdot 18H_2O$], ferric chloride ($FeCl_3$), or ferric sulfate ($FeSO_4 \cdot 7H_2O$) that may be used for solids capture or sludge thickening, orthophosphate may be precipitated. Orthophosphate also may be precipitated with

TABLE 7.1 Operational Problems Associated with a Nutrient Deficiency

Decreased cBOD removal efficiency
Decreased nBOD removal efficiency
Foam production and accumulation
Lack of adequate MLVSS production
Loss of solids
Settleability problems
Undesired growth of nutrient deficient filamentous organisms

TABLE 7.2 Nutrient Deficient Wastewaters for Nitrogen or Phosphorus

Wastewater	Nitrogen Deficient	Phosphorus Deficient
Bakery	X	
Beverage—malt	X	X
Beverage—distilled spirits	X	X
Beverage—wine	X	X
Beverage—soda drink/pop	X	X
Citrus	X	
Chemical		X
Coffee	X	
Coke ovens		X
Corn	X	
Cotton kerning	X	
Dairy—milk		X
Dairy—cottage cheese	X	
Food processing	X	X
Formaldehyde	X	X
Fruit and vegetable	X	X
Leather tanning		X
Petroleum refining		X
Pharmaceutical		X
Phenols	X	
Pulp and paper	X	X
Rag and rope	X	X
Textile	X	
Vinegar	X	X

TABLE 7.3 Nutrients Required by All Bacteria

Major nutrients:
C, Ca, Cl, H, K, N, Mg, Na, O, P, S
Minor nutrients:
B, Co, Cu, Cr, F, Fe, I, Mn, Mo, Ni, Se, Si, V, Zn

the lime [$Ca(OH)_2$] that is used for solids capture and sludge thickening. Because the metal phosphate salts are insoluble, they cannot enter bacterial cells and cannot be used by the bacteria.

Industrial wastewater that is not combined for treatment with domestic wastewater may be nutrient deficient. These wastewaters often contain large quantities

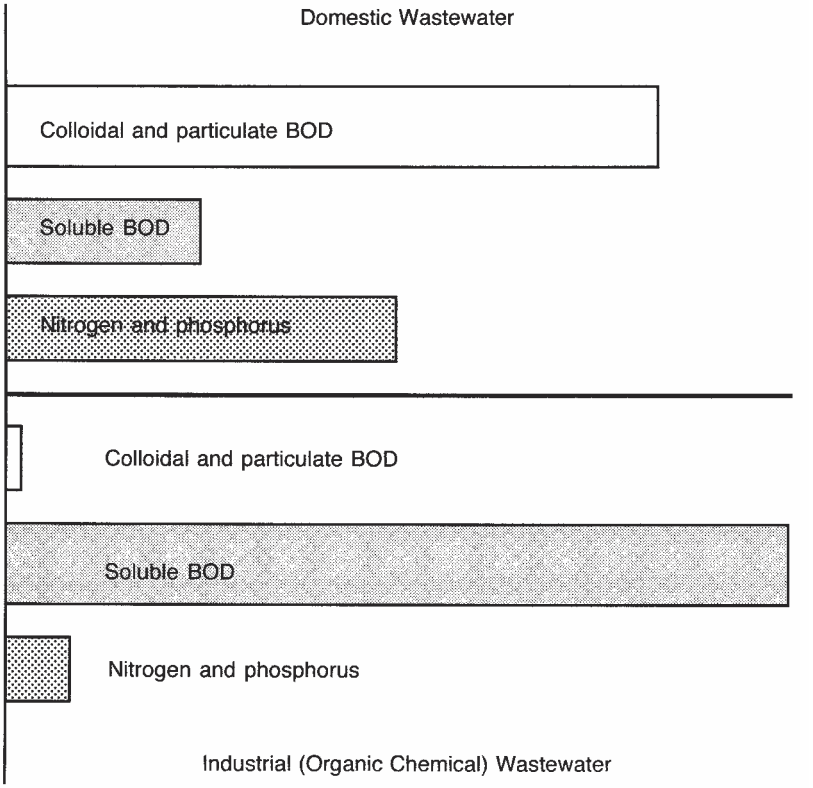

Figure 7.1 *Relative amounts of BODs and nutrients in domestic and industrial wastewaters. Domestic wastewater differs greatly in composition from most industrial wastewaters. Domestic wastewater contains much colloidal BOD and particulate BOD that degrade slowly in the aeration tank, whereas most industrial wastewaters such as organic chemical wastewater contain much soluble cBOD that degrades rapidly. Therefore, most industrial wastewaters exert a significant and immediate demand for dissolved oxygen and nutrients in the aeration tank compared with domestic wastewater. Also, domestic wastewater is not nutrient deficient, and many industrial wastewaters are nutrient deficient. Because most industrial wastewaters degrade quickly in the aeration tank and are nutrient deficient, nutrient deficiencies often are associated with the treatment of industrial wastewaters.*

of soluble cBOD that degrade quickly and demand relatively large quantities of nutrients. These wastewaters may be deficient for a major or minor nutrient.

Municipal wastewater contains domestic and industrial wastes. Depending on the quantity and quality of industrial wastes discharged to a municipal activated sludge process, the process may experience a nutrient deficiency for nitrogen or phosphorus. This would occur if the industrial wastes contain much soluble cBOD and little, if any, nitrogen or phosphorus.

A nutrient deficiency in an activated sludge process usually occurs during peak loading conditions. These conditions are periods of time in the aeration tank when large quantities of soluble cBOD are present. It is soluble cBOD that is degraded in the aeration tank, and it is the degradation of soluble cBOD that requires nutrients. Peak loading conditions occur when soluble cBOD from an industrial discharge enters the aeration tank.

TABLE 7.4 Indicators of Nutrient Deficiency

Growth of nutrient-deficient filamentous organisms
Production and accumulation of billowy white foam or greasy gray foam
Positive India ink reverse stain
BOD : N : P less than 100 : 5 : 1 in mixed liquor influent
scBOD : NH_4^+-N : HPO_4^{2-}-P in mixed liquor influent
Target values for readily available nutrients not satisfied in mixed liquor effluent

TABLE 7.5 Nutrient-Deficient Filamentous Organisms

Fungi	Type 021N
Haliscomenobacter hydrossis	Type 0041
Nocardioforms	Type 0675
Sphaerotilus natans	Type 1701
Thiothrix spp.	

There are several indicators of a nutrient deficiency in an activated sludge process (Table 7.4). These indicators include the undesired growth of nutrient-deficient filamentous organisms, the production and accumulation of nutrient-deficient foam, the presence of nutrient-deficient floc particles, the failure to satisfy desired BOD : N : P and soluble cBOD : NH_4^+ : HPO_4^{2-} values, and failure to satisfy nitrogen and phosphorus target values.

GROWTH OF NUTRIENT-DEFICIENT FILAMENTOUS ORGANISMS

There are several filamentous organisms that grow to relatively large numbers during a nutrient deficiency (Table 7.5). Two factors contribute to the increase in numbers of these filamentous organisms during a nutrient deficiency. First, the filamentous organisms that proliferate under a nutrient deficiency may require a smaller quantity of nutrients than the floc bacteria. Therefore, when nutrients become limited, the growth of the filamentous organisms is not hindered, but the growth of the floc bacteria is hindered. Second, because the filamentous organisms that proliferate during a nutrient deficiency have more surface area exposed to the bulk solution than floc bacteria, the filamentous organisms are able to obtain nutrients in adequate amounts when nutrients become limited in the bulk solution.

PRODUCTION AND ACCUMULATION OF NUTRIENT-DEFICIENT FOAM

Soluble cBOD is degraded inside bacterial cells. During a nutrient deficiency, some of the soluble cBOD cannot be degraded and is converted to an insoluble polysaccharide or slime that can be solubilized and degraded later when nutrients become available to the bacterial cells.

The slime is stored outside the bacterial cells. It adversely affects settleability and causes the production and accumulation of foam. The slime adversely affects settleability in several ways. First, the slime is insoluble in water and less dense than

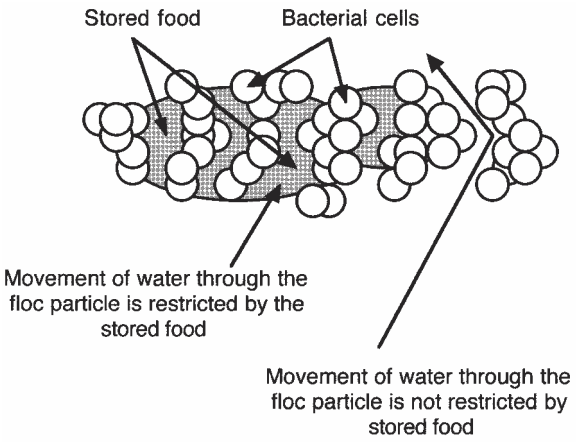

Figure 7.2 *Cross-sectional view of a nutrient deficient floc particle. During a nutrient deficiency, the bacterial cells in the floc particle absorb soluble cBOD. Because of the absence of an adequate amount of nutrients, the soluble cBOD cannot be degraded. The soluble cBOD is converted to insoluble cBOD and stored outside the bacterial cells in the floc particle channels. The insoluble cBOD prevents the movement of water through the floc particle and entraps air bubbles and gases. This results in a loss in settleability of solids. The entrapped air bubbles and gases contribute to foam production.*

water. Second, the slime causes a loss of compaction of floc bacteria as the bacterial cells separate slightly to accommodate the presence of stored food. Third, the slime fills the canals or openings in the floc particle, through which water must pass as the floc particle settles, and hinders the movement of water through the canals (Figure 7.2).

When the canals become plugged with stored food, air bubbles and gases become trapped in the canals. The entrapped air bubbles and gases contribute to a more buoyant floc particle and, under mixing action or aeration, the production and accumulation of foam.

There are two types of foam that may appear on the surface of an aeration tank during a nutrient deficiency. Billowy white foam usually appears when an activated sludge process is operating at a young sludge age, whereas greasy gray foam is typical at an old sludge age. The slime and the entrapped air bubbles and gases are responsible for billowy white foam. The foam becomes greasy gray during an old sludge age because of the accumulation of biological lipids that are secreted from a large and aging population of organisms.

INDIA INK REVERSE STAIN

An India ink reverse stain reveals the relative amount of stored food or slime in a floc particle (Appendix II). Aqueous India ink has microscopic carbon black particles in suspension. When India ink and mixed liquor are stirred together and examined as a wet mount under phase-contrast microscopy, the relative amount of stored food or probability of a nutrient deficiency may be revealed. Under phase-contrast microscopy, areas of the floc particle that contain carbon black particles appear

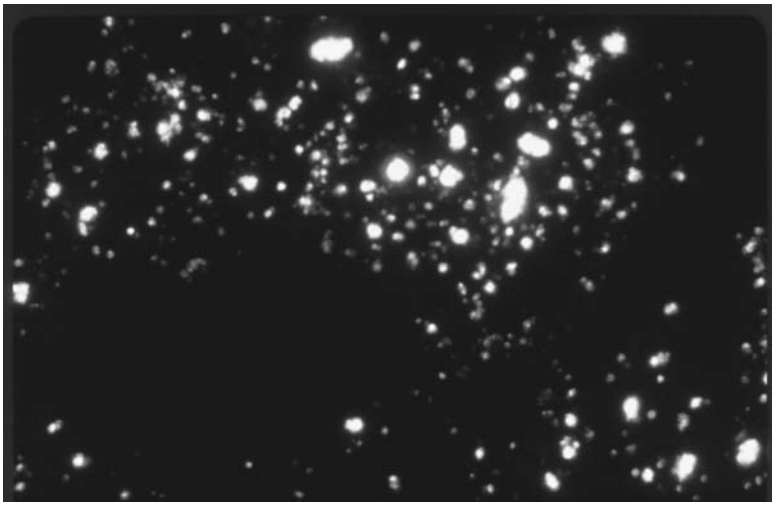

Figure 7.3 *Negative India ink reverse stain. When aqueous India ink is mixed with floc particles from a nutrient-adequate environment, the carbon black particles within the India ink penetrate rapidly throughout the floc particle. Only a small amount of the area of the floc particles is white because of the presence of a small amount of stored food or insoluble cBOD. This is a negative India ink reverse stain.*

black or golden brown whereas areas of the floc particle that do not contain carbon black particles appear white.

When a small amount of food is stored in a floc particle, as would be the condition during a nutrient-adequate condition, a small amount of the area of the floc particle is white under phase-contrast microscopy (Figure 7.3). The white area occurs because carbon black particles are absent in the area. The absence of carbon black particles is due to the presence of stored food that hinders the movement of the carbon black particle into the floc particle. When a large amount of food is stored in a floc particle, as would be the condition during a nutrient deficiency, a large amount of the area of the floc particle is white under phase-contrast microscopy (Figure 7.4). A microscopic evaluation of floc particles under an India ink reverse stain can be used to evaluate the probability of a nutrient deficiency if the floc particle responds positively to the India ink reverse stain.

BOD : N : P

Engineering studies during the 1950s revealed that for every 100 parts (mg/l or lbs) of total BOD degraded over 5 days under controlled laboratory conditions, 5 parts of total nitrogen and one part of total phosphorus were required for its degradation. These studies used settled sewage or primary clarifier effluent. The amounts of nitrogen and phosphorus are representative of their approximate percent composition of the dry weight of a typical bacterial cell (Table 7.6). The approximate percent composition for nitrogen and phosphorus is 15% and 3%, respectively, representing a 15 : 3 or 5 : 1 ratio. If the ratio BOD : N : P is satisfied at all times in the primary

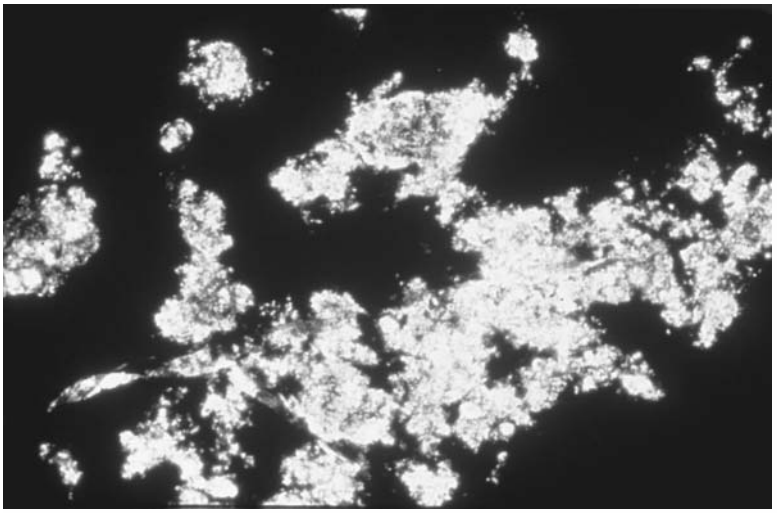

Figure 7.4 *Positive India ink reverse stain. When aqueous India ink is mixed with floc particles from a nutrient-deficient environment, the carbon black particles within the India ink cannot penetrate throughout the floc particle. Their movement is hindered by the presence of stored food or insoluble cBOD. The majority of the area of the floc particle under a nutrient-deficient condition is white because of the presence of a large amount of stored food or insoluble cBOD.*

TABLE 7.6 Approximate Percent Composition of Major Nutrients in Bacterial Cells on Dry Weight Basis

Nutrient	Approximate Composition
Carbon	50%
Oxygen	20%
Nitrogen	15%
Hydrogen	8%
Phosphorus	3%
Sulfur	1%
Potassium	1%
Others	2%

TABLE 7.7 Types of BOD and the Rate of Degradation in the Activated Sludge Process

Type of BOD	Acronym	Rate of Degradation
Colloidal BOD	coBOD	Most coBOD compounds degrade slowly
Nitrogenous BOD	nBOD	Quickly after scBOD has been adequately degraded
Particulate BOD	pBOD	Most pBOD compounds degrade slowly
Soluble carbonaceous BOD	scBOD	Most scBOD degrade quickly

clarifier effluent or mixed liquor influent, adequate nutrients should be available in the aeration tank.

The BOD test used to provide the ratio of 100 :5:1 does not differentiate between the different types of BOD (Table 7.7) and the nitrogenous compounds

and phosphorous compounds that release nitrogen and phosphorus for bacterial use during the degradation of BOD. Also, the BOD test does not reveal the rate of degradation of BOD or the hydraulic retention time (HRT) experienced in the aeration tank used for the degradation of BOD. Therefore, the ratio of 100:5:1 for primary clarifier effluent BOD, total nitrogen, and total phosphorus should be used as a guideline.

SOLUBLE cBOD, NH_4^+–N, AND HPO_4^{2-}–P

The BOD:N:P ratio of 100:5:1 to determine the presence or absence of adequate amounts of nitrogen and phosphorus in an aeration tank can be improved upon as a guideline when the three components of the ratio are modified. Because only soluble cBOD is degraded in an aeration tank and exerts a significant and immediate demand for nutrients, soluble cBOD may be used in lieu of total BOD.

When soluble cBOD is degraded in an aeration tank, the nutrients that are used first to degrade the soluble cBOD are readily available nutrients. The bacteria select these nutrients first because they move or diffuse from higher concentrations outside the cell to lower concentrations inside the cell. The diffusion of readily available nutrients occurs quickly and without an expenditure of cellular energy. Readily available nutrients are ammoniacal-nitrogen (NH_4^+–N) and orthophosphate-phosphorus (HPO_4^{2-}–P). Therefore, consideration should be given to the use of NH_4^+–N rather than total nitrogen and HPO_4^{2-}–P rather than total phosphorus.

TARGET VALUES FOR READILY AVAILABLE NUTRIENTS

Because of changes in HRT within an aeration tank and the occurrence of peak loading conditions, the amount of readily available nutrients that are needed in an aeration tank can change significantly throughout the day. Readily available nutrients are needed in largest quantities when the largest quantity of soluble cBOD is present in the aeration tank. This occurs when HRTs are long or industrial wastewater is present.

With increasing HRT, more and more particulate BOD and colloidal BOD are solubilized through bacterial activity. The solubilization of particulate BOD and colloidal BOD results in the production of soluble cBOD and an increased demand for more readily available nutrients. With few exceptions, industrial wastewater contains much soluble cBOD. The time during which large quantities of industrial wastewater are in the aeration tank represents peak loading conditions.

During peak loading conditions, the mixed liquor effluent filtrate from an in-line aeration tank should be sampled periodically and tested to ensure that target value concentrations of readily available nutrients are present (Table 7.8). Recommended target value concentrations are 1.0 mg/l for NH_4^+–N and 0.5 mg/l for HPO_4^{2-}–P. For activated sludge processes that nitrify completely and have an NH_4^+–N concentration <1.0 mg/l in the mixed liquor effluent, a nitrate-nitrogen (NO_3^-–N) target value concentration of 3.0 mg/l can be used in lieu of the NH_4^+–N concentration. Nitrate-nitrogen is approximately 30% available for a nitrogen nutrient, whereas ammoni-

TABLE 7.8 Recommended Target Values for Readily Available Nutrients

Nutrient	Form of Nutrient and Concentration
Nitrogen	1.0 mg/l NH_4–N or 3.0 mg/ NO_3^-–N
Phosphorus	0.5 mg/l HPO_4^{2-}–P

TABLE 7.9 Chemical Compounds Suitable for Nutrient Addition

Nutrient needed	Chemical Compound	
	Name	Formula
Nitrogen	Anhydrous ammonia	NH_3
	Aqua ammonia	NH_4OH
	Ammonium bicarbonate	NH_4HCO_3
	Ammonium carbonate	$(NH_4)_2CO_3$
	Ammonium chloride	NH_4Cl
	Ammonium sulfate	$(NH_4)_2SO_4$
Phosphorus	Trisodium phosphate	Na_3PO_4
	Disodium phosphate	Na_2HPO_4
	Monosodium phosphate	NaH_2PO_4
	Sodium hexametaphosphate	$Na_3(PO_3)_6$
	Sodium tripolyphosphate	$Na_5P_3O_{10}$
	Tetrasodium pyrophosphate	$Na_4P_2O_7$
	Phosphoric acid	H_3PO_4
Nitrogen/phosphorus	Ammonium phosphate	$NH_4H_2PO_4$

acal-nitrogen is 100% available for a nitrogen nutrient. Therefore, 3 mg/l of NO_3^-–N is equivalent to 1.0 mg/l of NH_4^+–N.

Target values for readily available nutrients should be obtained in the absence of toxicity. During toxic events, enzymatic activity or the degradation of soluble cBOD is arrested or hindered. When enzymatic activity is adversely affected by toxic events, soluble cBOD is not degraded or is inefficiently degraded. Because of the decrease in soluble cBOD degradation, the bacteria remove smaller quantities of readily available nutrients from the mixed liquor. Therefore, readily available nutrients should be present in the mixed liquor effluent filtrate at concentrations much greater than their recommended target values.

CONTROL

To correct for a nutrient deficiency in an aeration tank, an appropriate nitrogenous compound or phosphorous compound should be added to the primary clarifier effluent or mixed liquor influent (Table 7.9). The amount of the compound added should satisfy the selected operational measure for ensuring adequate nutrients. Nutrients should never be added in quantities that would cause a final effluent violation for a nitrogen or phosphorus limit.

Before chemicals are purchased and added to the primary clarifier effluent or

aeration tank influent to correct for a nutrient deficiency, an alternate measure may be used. If a municipal activated sludge process is experiencing a nutrient deficiency, the industrial waste stream responsible for the deficiency should be identified and the industry should be required to correct for the nutrient deficiency. Recycle streams within the treatment plant should be tested for the presence of readily available nutrients that can be used to correct for a nutrient deficiency.

Recycle streams that may be used for nutrient addition include decant from digesters, filtrate from belt filter presses, and centrate from centrifuges. These recycle streams contain ammoniacal-nitrogen and orthophosphate-phosphorus that has been released from dead bacterial cells. If sufficient ammoniacal-nitrogen and orthophosphate-phosphorus are available, the timing of digester decanting operations and sludge dewatering practices may be scheduled so that these recycle streams enter the aeration tanks when readily available nutrients are needed. However, the recycle streams also should be examined to ensure that excess soluble cBOD is not present. The presence of excess soluble cBOD in the recycle stream would place a significant dissolved oxygen and nutrient demand on the aeration tank.

8

Denitrification

A common problem in secondary clarifiers that results in settleability problems and the loss of solids is denitrification. Also known as "blanket rising," "clumping," and "rising sludge," denitrification occurs in secondary clarifiers when facultative anaerobic bacteria or denitrifying bacteria in the settled solids use nitrate ions (NO_3^-) or nitrite ions (NO_2^-) to degrade soluble cBOD.

Facultative anaerobic bacteria make-up approximately 80% of the bacteria within the solids or floc particles. Groups or genera of bacteria in the activated sludge that have large numbers of denitrifying bacteria are *Alcaligens*, *Bacillus*, and *Pseudomonas*. Denitrifying bacteria are capable of using dissolved oxygen or free molecular oxygen (O_2), if it is available, and NO_3^- or NO_2^-, if free molecular oxygen is not available or an oxygen gradient is established across a floc particle (Figure 8.1).

Although the presence of NO_3^- and NO_2^- in the secondary clarifier may be due to an industrial discharge (Table 8.1), it usually is due to the occurrence of nitrification in the aeration tank. Nitrification is the oxidation or addition of oxygen to ammonium ions (NH_4^+) to produce nitrite ions and the oxidation of nitrite ions to produce nitrate ions. The nitrifying bacteria *Nitrosomonas* and *Nitrobacter* biologically mediate the nitrification of ammonium ions and nitrite ions, respectively.

Soluble cBOD in the secondary clarifier serves as the substrate for denitrifying bacteria. It is the quantity of soluble cBOD that drives denitrification. With increasing quantities of soluble cBOD, any residual dissolved oxygen is more rapidly removed by bacterial activity and denitrification occurs more quickly.

When denitrification occurs, several gases are produced as NO_3^- and NO_2^- are used to degrade soluble cBOD. These gases are molecular nitrogen (N_2), nitrous oxide (N_2O), and carbon dioxide (CO_2). The gases N_2 and N_2O are insoluble in wastewater and escape to the atmosphere or become entrapped in the solids (Figure 8.2). Carbon dioxide is slightly soluble in wastewater. When CO_2 dissolves in wastewater, carbonic acid (H_2CO_3) is formed (Equation 8.1). Some of the carbonic acid

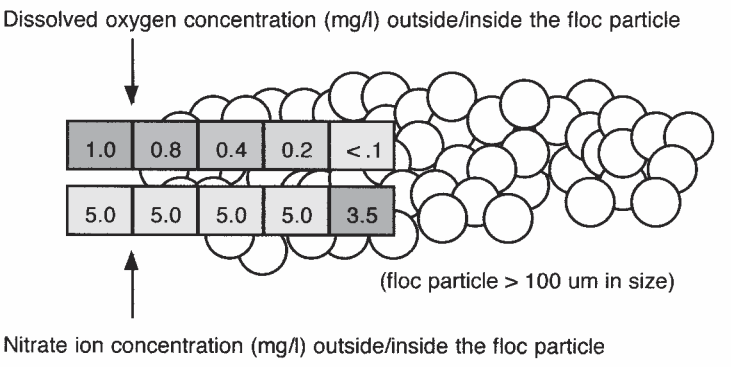

Figure 8.1 *Cross-sectional view of an oxygen gradient across a floc particle. An oxygen gradient across a floc particle occurs when dissolved oxygen cannot penetrate to the core of the floc particle. When dissolved oxygen is not present, the bacteria in the core of the floc particle use nitrate ions to degrade soluble cBOD. This can occur when the size of the floc particle is ≥100 μm and the dissolved oxygen concentration outside the floc particle is ≤1.0 mg/l. In the presence of an oxygen gradient, dissolved oxygen can be measured and denitrification can occur.*

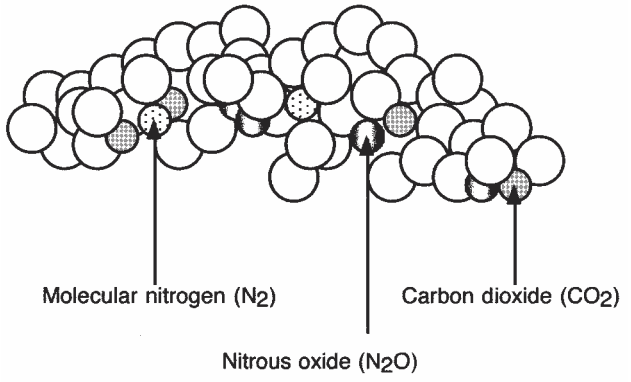

Figure 8.2 *Cross-sectional view of entrapped gases in a denitrifying floc particle. When denitrification occurs in floc particles, three gases are produced and released by the floc bacteria. These gases are molecular nitrogen (N_2), nitrous oxide (N_2O), and carbon dioxide (CO_2). Molecular nitrogen and nitrous oxide are insoluble in wastewater. Some of the carbon dioxide is insoluble in wastewater. The gases that do not dissolve in the wastewater may become entrapped in the floc particles. The entrapped gases make the floc particles buoyant. This buoyancy contributes to settleability problems and loss of solids.*

TABLE 8.1 Industrial Sources of Nitrite Ions and Nitrate Ions

Industrial discharge	Nitrite ions	Nitrate ions
Corrosion inhibitor	X	
Leachate (pretreated)	X	X
Meat (flavoring)		X
Meat (preservative)	X	
Meat (pretreated)	X	X
Steel	X	X

TABLE 8.2 Indicators of Denitrification

Presence of gas bubbles (N_2, N_2O, and CO_2)
Presence of dark sludge rising
Increase in alkalinity across the secondary clarifier
Increase in pH across the secondary clarifier
Reduction in NO_2^- across the secondary clarifier
Reduction in NO_3^- across the secondary clarifier
Reduction in redox potential across the secondary clarifier

TABLE 8.3 Indicators of Nitrification

Decrease in alkalinity in the aeration tank
Decrease in pH in the aeration tank
Growth of algae or duckweed in the secondary clarifier
Increase in NO_2^- across the aeration tank
Increase in NO_3^- across the aeration tank
Presence of *Epistylis* spp. and *Vorticella* spp. in the aeration tank
Presence of a high dissolved oxygen concentration (>2 mg/l)
Presence of a high MCRT or sludge age (>8 days)
Presence of a high MLVSS concentration (>2000 mg/l)

disassociates in the wastewater to form bicarbonate alkalinity (HCO_3^-) (Equation 8.2). If CO_2 does not dissolve in wastewater, it either escapes to the atmosphere or becomes entrapped in the solids.

$$CO_2 + H_2O \rightarrow H_2CO_3 \tag{8.1}$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \tag{8.2}$$

The entrapment of gases in the solids renders the solids buoyant. The buoyant nature of the solids results in poor compaction of solids and a loss of settleability. When a significant amount of N_2, N_2O, and CO_2 has been entrapped in the solids, the solids rise to the surface in large, dark clumps.

There are numerous indicators of denitrification in the activated sludge process (Table 8.2). Because nearly all activated sludge processes nitrify in order to denitrify, indicators of nitrification also support the occurrence of denitrification (Table 8.3). Indicators of denitrification and nitrification may be biological, chemical, or physical.

INDICATORS OF DENITRIFICATION

Indicators of denitrification include the presence of numerous gas bubbles, dark clumps of rising solids, and appropriate operational data. When denitrification occurs, gas bubbles produced through the release of N_2, N_2O, and CO_2 can be observed rising to the surface of the secondary clarifier, rising to the surface of the solids settleometer, and entrapped within floc particles and filamentous organisms.

TABLE 8.4 Denitrification and Redox Potential

Redox Potential	Microbial Event
≥+150	Bacterial degradation of cBOD with free molecular oxygen Nitrification of NH_4^+ and NO_2^- with free molecular oxygen
+150 to −150	Bacterial degradation of cBOD with NO_2^- and NO_3^-
≤−150 mV	Bacterial degradation of cBOD with SO_4^{2-}

Bubbles of gas may be found rising to the surface of the clarifier and the surface of a solids settleometer or attached to the surface or the rising solids. Often when the rising solids reach the surface they break apart and numerous bubbles of gas may be released. Bubbles of gas usually are produced in a settleometer from 30 to 60 minutes after the start of the settleability test. During denitrification, large clumps of dark sludge can be found rising from the bottom of the secondary clarifier and settleometer.

When denitrification occurs in the secondary clarifier, alkalinity is returned to the clarifier through the release of hydroxyl ions (OH^-) and carbon dioxide (Equation 8.3). Hydroxyl ions contribute directly to alkalinity, whereas carbon dioxide contributes indirectly to alkalinity through the production of bicarbonate alkalinity.

$$6NO_3^- + 5CH_3OH \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^- \quad (8.3)$$

When denitrification occurs in the secondary clarifier, alkalinity increases across the clarifier from influent to effluent ends. If sufficient alkalinity is returned to the secondary clarifier, pH across the clarifier may increase. Because nitrate ions and nitrite ions are used during denitrification, the concentration of these ions decreases across the secondary clarifier.

The presence of nitrite ions and nitrate ions contributes to redox potential (Table 8.4). Denitrification occurs in the redox range of +150 to –150 mV. As denitrification occurs and nitrate ions and nitrite ions are reduced in concentration, the redox potential drops or becomes more negative.

INDICATORS OF NITRIFICATION

With few exceptions, activated sludge processes that denitrify must nitrify. Nitrification provides the nitrate ions and nitrite ions that are used during nitrification. For an activated sludge process to nitrify, it must grow a relatively large number of slowly reproducing and poorly flocculating nitrifying bacteria. Therefore, an activated sludge process that denitrifies should have operational data indicative of nitrification.

Activated sludge processes that nitrify produce NO_3^-. These ions serve as the principal nitrogen nutrient for algae and duckweed. Therefore, the presence of algae or duckweed in secondary clarifiers is an indicator of nitrification.

Because nitrification occurs when the activated sludge process is stable, two genera of stalk ciliated protozoa may be present in relatively large numbers. These

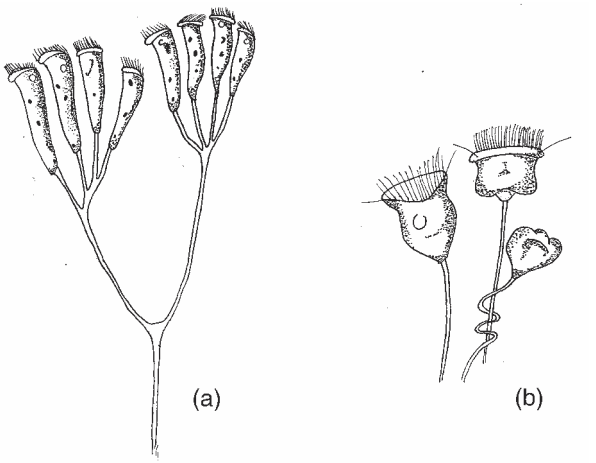

Figure 8.3 *Epistylis and Vorticella. Protozoa that are observed in relatively large numbers in activated sludge processes that nitrify efficiently are the stalked ciliates* Epistylis *(a) and* Vorticella *(b). These protozoa may nitrify or may simply reflect operational conditions that are optimal for nitrification to occur.*

genera are *Epistylis* and *Vorticella* (Figure 8.3). These organisms may nitrify significantly or may simply be present when conditions are optimal for nitrification.

For an activated sludge process to maintain a large and active population of nitrifying bacteria, several critical operational factors must be satisfied. These factors include a high sludge age or MCRT, a high MLVSS, and a relatively high dissolved oxygen concentration in the aeration tank.

TEMPERATURE EFFECT ON DENITRIFICATION AND NITRIFICATION

With increasing wastewater temperature, denitrification and nitrification occur more easily. This usually occurs at temperatures >16°C. At wastewater temperatures >16°C, over 50% of the ability of the activated sludge process to nitrify is achieved.

Increasing wastewater temperature results in an increase in bacterial activity, a rapid depletion of dissolved oxygen concentration through bacterial activity, and rapid occurrence of denitrification. Also, warm wastewater has less affinity for dissolved oxygen. The lower affinity for oxygen in warm wastewater also contributes to the rapid occurrence of denitrification.

CONTROL

If the activated sludge process is not required to nitrify, then operational conditions may be changed to terminate nitrification and prevent the production of nitrate ions and nitrite ions. To prevent nitrification, the dissolved oxygen concentration in the aeration tank may be lowered, the HRT in the aeration tank may be decreased, or the organic loading to an aeration tank may be increased. Placing an aeration tank off-line decreases the HRT and increases the organic loading in the remaining in-line aeration tanks.

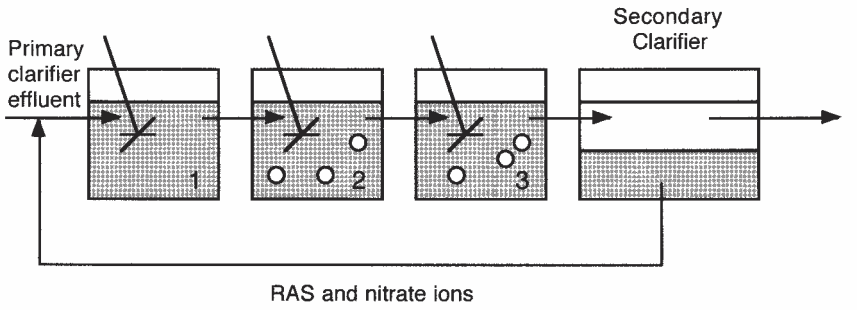

Figure 8.4 *Use of an anoxic tank in plug-flow mode of operation to control denitrification. Denitrification in the secondary clarifier may be controlled by using an anoxic tank in plug-flow mode of operation. In this mode of operation, solids and nitrate ions are removed from the floor of the secondary clarifier at an increased RAS rate. The solids and nitrate ions are returned to the first aeration tank. The tank is mixed and either not aerated or aerated only slightly to ensure mixing. The primary clarifier effluent that contains soluble cBOD is fed to the first aeration tank. The solids (bacteria) in the first tank along with nitrate ions and soluble cBOD are responsible for the production of an anoxic condition. Denitrification occurs under an anoxic condition.*

If nitrification in an activated sludge process is required or desired, the mode of operation may be changed to plug-flow (Figure 8.4). The first aeration tank in plug-flow is used as an anoxic zone. Here, the bacteria in the aeration tank are mixed with nitrate ions and nitrite ions from the RAS and soluble cBOD in the influent. In the anoxic zone, the bacteria, the lack of oxygen, the presence of nitrate ions and nitrite ions, and the soluble cBOD promote denitrification.

Regardless of the cause of denitrification in the secondary clarifier, increasing the RAS rate can control denitrification. Increase in the RAS rate removes the solids from the floor of the secondary clarifier before the sludge blanket is deoxygenated. Solids in the secondary clarifier also may be thickened with a metal salt or polymer and removed more rapidly from the floor of the secondary clarifier.

9

Sheared Floc Particles

Excessive turbulence in the activated sludge process may result in the production of sheared floc particles and the loss of fine solids. Common sources of excessive turbulence are surface aerators, high rates of coarse aeration, RAS pumps, and high rates of RAS. These sources of excessive turbulence place considerable physical stress on the floc particles and the community of stalk ciliated protozoa.

In the presence of excessive turbulence, fine solids in the bulk solution are not easily adsorbed to floc particles and fine solids on the floc particles are torn free. Also, the perimeter of the floc particles is torn by the turbulence. As the perimeter of the floc particles is torn, more and more bacteria are lost from the floc particles to the bulk solution.

When exposed to excessive turbulence, the enlarged anterior portion of stalk ciliated protozoa is ripped from the slender posterior portion of the organism (Figure 9.1). Often, the anterior portion may be found free-floating in the bulk solution (Figure 9.2), and the posterior portion may be found attached to a floc particle (Figure 9.3).

Excessive turbulence is highly undesired in the activated sludge process. The loss of fine solids through excessive turbulence represents an increase in total suspended solids (TSS) in the final effluent. The increase may result in an effluent permit violation for TSS. A significant portion of the fine solids consists of bacteria that degrade or remove BOD. Therefore, significant losses in treatment efficiencies for cBOD removal and nBOD removal may occur. Finally, increased operational costs may occur if metal salts or polymers are used to capture fine solids in the secondary clarifier.

INDICATORS OF EXCESSIVE TURBULENCE

There are several microscopic indicators of excessive turbulence in the activated sludge process (Table 9.1). These indicators include an increase in the amount of

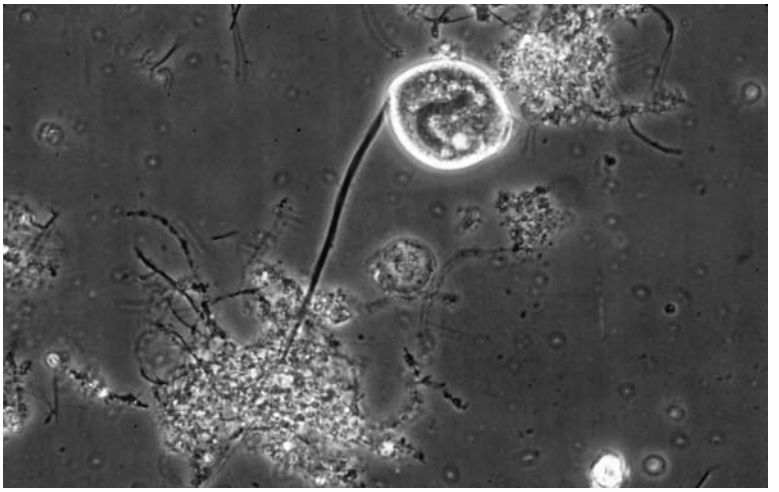

Figure 9.1 *Stalk ciliated protozoa. Stalk ciliated protozoa possess an enlarged anterior portion or "head" that is attached to a slender posterior portion or "tail." In the presence of excessive turbulence, the "head" of the protozoa may be sheared from the "tail."*

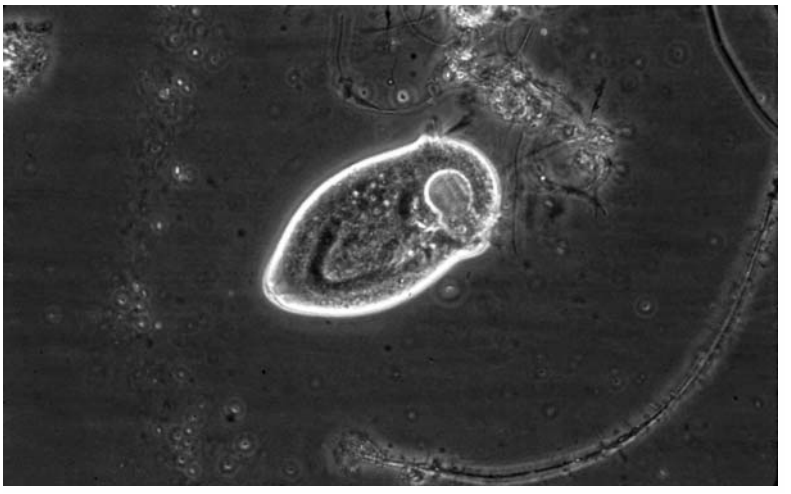

Figure 9.2 *Enlarged anterior portion of a stalk ciliated protozoa. In the presence of excess turbulence, the enlarged anterior portion of stalk ciliated protozoa may be sheared from the slender posterior portion of the protozoa. The sheared anterior portion may be adsorbed to a floc particle or may float freely in the bulk solution.*

dispersed growth, the presence of small and irregularly shaped floc particles as the dominant size and shape of floc particles, and numerous sheared, stalk ciliated protozoa.

In a mature activated sludge process that does not experience excessive turbulence, very little dispersed growth should be present in the bulk solution. The relative abundance rating for dispersed growth in this process would be "insignificant"

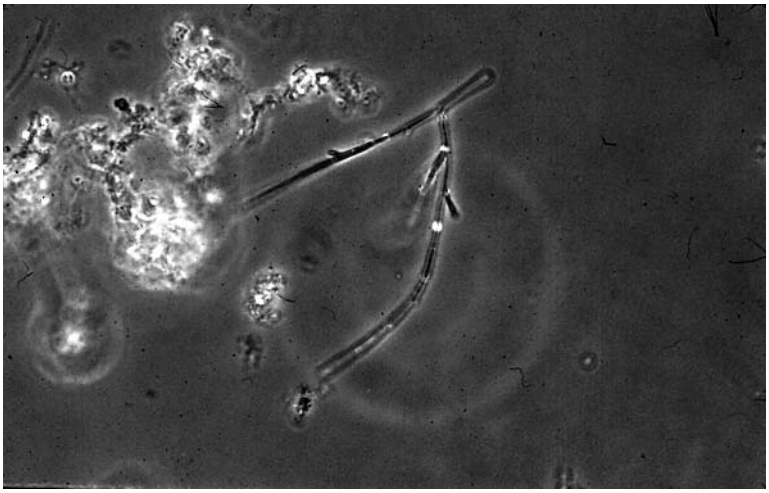

Figure 9.3 *Slender posterior portions of stalk ciliated protozoa. The sheared slender posterior portions of stalk ciliated protozoa can be found attached to a small portion of a sheared floc particle. The posterior portion of the protozoa cannot grow a new anterior portion, and the anterior portion of the protozoa cannot grow a new posterior portion.*

TABLE 9.1 Indicators of Excessive Turbulence

Increase in dispersed growth in the bulk solution to a relative abundance rating of "1" or "2"
Dominance of small, irregularly shaped floc particles
Numerous sheared stalk ciliated protozoa

or "0" (Figure 9.4) on a scale of "0" to "2" (Table 9.2). However, in the presence of excessive turbulence, the amount of dispersed growth increases considerably. The relative abundance rating for dispersed growth in the presence of excessive turbulence would be "significant" or "1" (Figure 9.5) or "excessive" or "2" (Figure 9.6).

In a mature activated sludge process, medium (150–500 μm) and large (>500 μm) floc particles usually are the dominant-size particles. Because of the presence of significant filamentous growth within the floc particles and extending from the perimeter of the floc particles, these particles should be irregular in shape. However, in the presence of excessive turbulence, the floc particles are repeatedly torn. This results in the production of numerous small (<150 μm) and irregularly shaped floc particles.

In most activated sludge processes it is common to find a small percentage (<5%) of sheared stalk ciliated protozoa. However, in the presence of excessive turbulence the percentage of sheared stalk ciliated protozoa should be much higher. With increasing turbulence, the percentage of sheared stalk ciliated protozoa increases.

Although the anterior portion of the stalk ciliated protozoa is more easily recognized than the posterior portion of the protozoa, the anterior portion is buoyant and, unless adsorbed to a floc particle, it is lost from the activated sludge process in the final effluent. Therefore, the posterior portions of stalk ciliated protozoa that

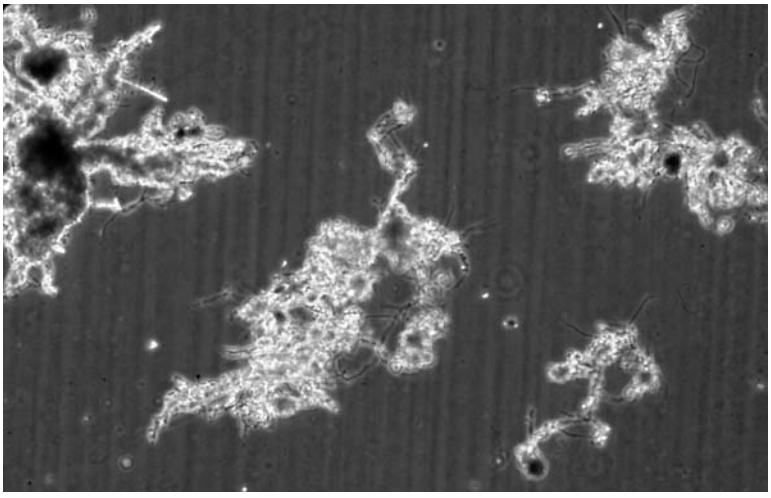

Figure 9.4 *Dispersed growth at "0" rating. At 100× total power magnification, the amount of dispersed growth should be "insignificant" or <20 cells per field of view. Dispersed growth at a rating of "insignificant" or "0" is expected in a healthy activated sludge process.*

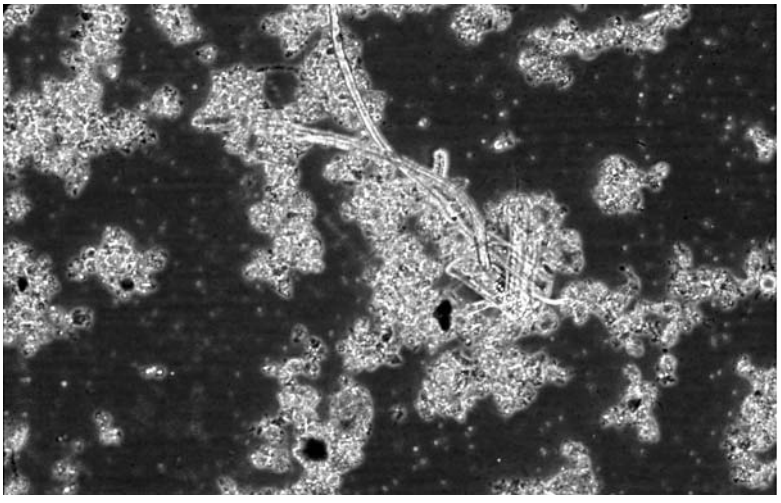

Figure 9.5 *Dispersed growth at "1" rating. At 100× total power magnification, the amount of dispersed growth should be "significant" or tens of cells per field of view. Dispersed growth at a rating of "significant" or "1" is expected in an activated sludge process that experiences interruption of floc formation through excess turbulence.*

TABLE 9.2 Relative Abundance Ratings for Dispersed Growth

Rating	Term	Description
"0"	Insignificant	<20 cells in bulk solution per field of view at 100× total power magnification
"1"	Significant	Tens of cells (20–99) in the bulk solution per field of view at 100× total power magnification
"2"	Excessive	Hundreds of cells (>100) in the bulk solution per field of view at 100× total power magnification

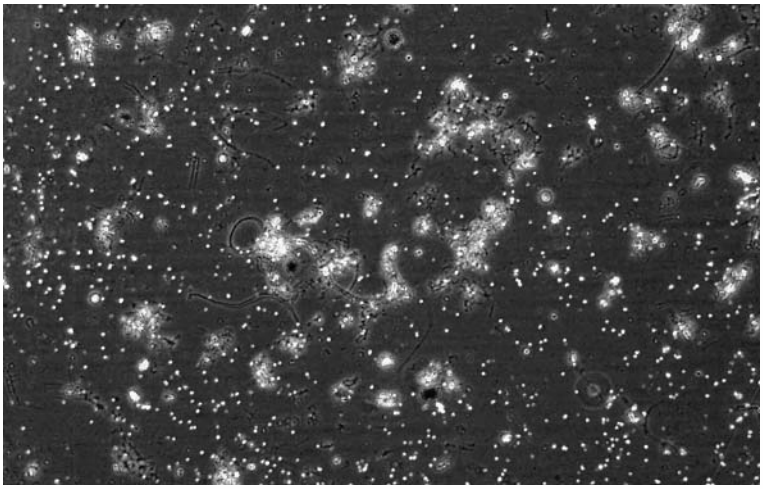

Figure 9.6 *Dispersed growth at "2" rating. At 100× total power magnification, the amount of dispersed growth should be "excessive" or hundreds of cells per field of view. Dispersed growth at a rating of "excessive" or "2" is expected in an activated sludge process that experiences interruption of floc formation through excess turbulence.*

remain attached to floc particles should be counted to determine the percentage of sheared stalk ciliated protozoa.

There are some industrial wastes, for example, *t*-butanol and phenolic compounds, that attack the cellular material that holds together the anterior and posterior portions of a stalk ciliated protozoa. These industrial wastes cause the anterior portion of the stalk ciliated protozoa to float free of the posterior portion.

Stalk ciliated protozoa cannot repair or replaced a sheared anterior or posterior portion. The anterior portion of the organism cannot grow a posterior portion, and the posterior portion cannot grow an anterior portion.

CONTROL

To identify the source of excessive turbulence in the activated sludge process, wastewater samples before and after the suspect equipment or treatment tank should be collected and examined for indicators of excessive turbulence. For example, wastewater samples before and after the RAS pump or samples after the RAS pump at different RAS rates can be used to determine whether the RAS pump or the RAS rate is responsible for the production and loss of fine solids. Also, wastewater samples before and after aeration tanks can be used to determine whether excessive turbulence is occurring within the aeration tanks.

If the production and loss of fine solids through excessive turbulence are a significant operational problem, then an appropriate corrective measure should be used (Table 9.3). The long-term corrective measure for the production and loss of fine solids is to identify the source of excessive turbulence and repair, replace, or remove from service the mechanical unit responsible for the excessive turbulence.

TABLE 9.3 Corrective Measures for Loss of Fine Solids Produced Through Excessive Turbulence

Repair, replace, or remove from service the mechanical unit responsible for the excessive turbulence
Addition of polymers to secondary clarifier influent
Addition of metal salts to the secondary clarifier influent
Use of plug-flow mode of operation and flocculation tank

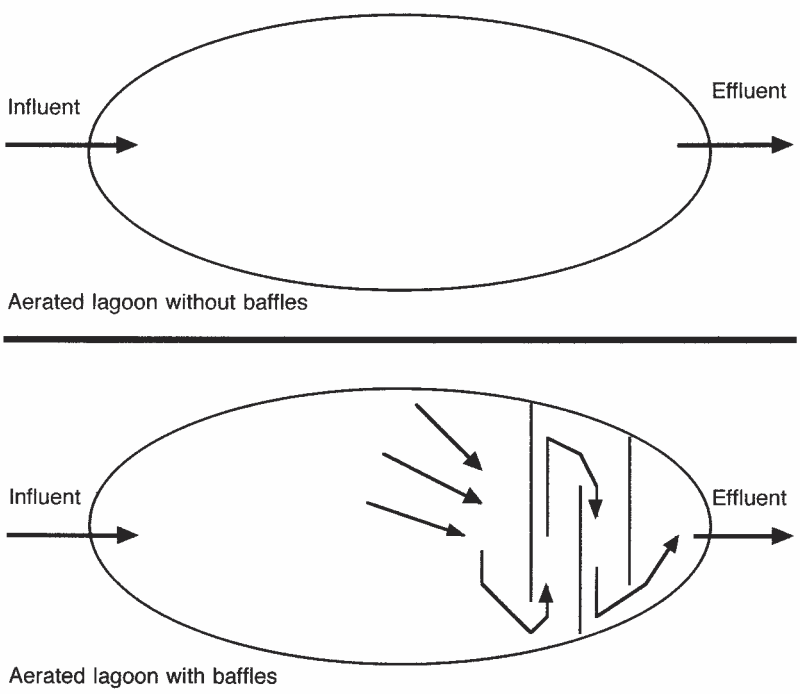

Figure 9.7 *Use of baffles in an aerated lagoon to correct for shearing action. By installing baffles or blankets at the effluent end of an aerated lagoon the wastewater across the lagoon is forced to flow in a serpentine pattern. This change in flow pattern may permit an improvement in floc formation or may reduce the quantity of metal salts or polymers used to capture fine solids.*

However, if the long-term solution is cost prohibitive or not easily identified, then an alternate corrective measure should be used.

Alternate corrective measures consist of the use of chemical addition to capture fine solids and add weight and density to floc particles and, if possible, the use of baffles in an aerated lagoon (Figure 9.7) or plug-flow mode of operation (Figure 9.8). The use of baffles and change in mode of operation are intended to provide a flocculation zone between the turbulent aeration tank or lagoons and the quiescent secondary clarifier.

Chemicals commonly used to correct for the production and loss of fine solids include cationic polymers and metal salts. These chemicals may be used as a single-component system—polymer or metal salt only—or a dual-component system—

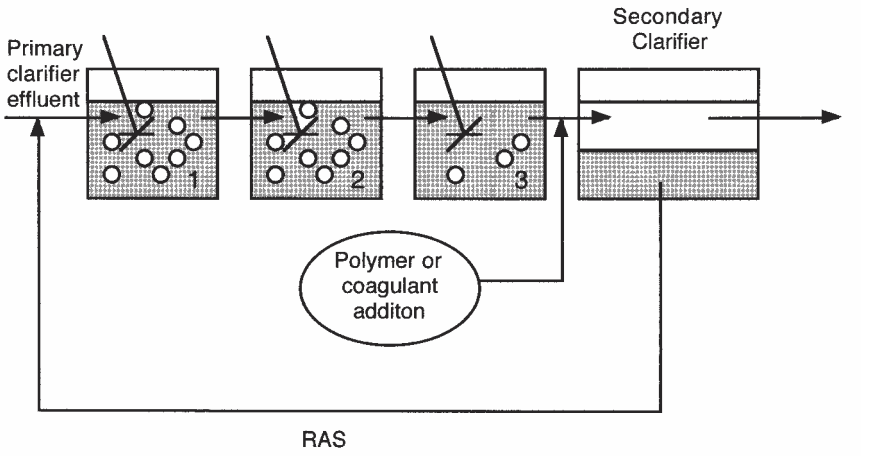

Figure 9.8 *Use of a flocculation tank in plug-flow mode of operation. Using a flocculation tank in plug-flow mode of operation may control the loss of fine solids in the secondary clarifier. In this mode of operation, the last aeration tank is used as the flocculation tank. In this tank minimal mixing and minimal aeration (at least 1.0 mg/l) are provided to establish the smallest amount of turbulence as possible. With reduced turbulence, fine solids may be adsorbed by the floc particles. With the use of a flocculation tank ,the use of metals salts or polymers in the aeration tank effluent to capture fine solids may be reduced or eliminated. With a reduced dissolved oxygen level in the flocculation tank, the activated sludge process should be periodically monitored for the undesired growth of low-dissolved-oxygen filamentous organisms.*

polymer and metal salt. Regardless of which chemicals are used, they should be tested in the laboratory with the mixed liquor effluent to ensure proper polymer charge, weight, and dose and proper metal salt dose. Chemical addition should be made at the mixed liquor effluent or secondary clarifier influent.

The addition of polymers captures or brings together many fine solids or joins the solids to the floc particles. Polymers also help to improve the density of floc particles. The addition of metal salts captures some solids by joining them to the floc particles. Metal salts help to improve the density of floc particles and also add weight to the floc particles. Improved density and increased weight are important in settling small, sheared floc particles in the secondary clarifier.

If the design of the activated sludge process allows the use of the plug-flow mode of operation, this mode of operation may be used to correct for the production and loss of solids. In this mode of operation, the last aeration tank in series may be used as a flocculation tank. If the aeration tanks upstream of the flocculation tank are able to adequately treat the influent loading, then minimal mixing and minimal aeration (≥1 mg/l dissolved oxygen) should be maintained in the flocculation tank to allow the solids and floc particles to naturally join together. If the flocculation is successful, then the use of polymers and metal salts may be eliminated or reduced.

10

Dispersed Floc Particles

The presence of soaps and detergents in the activated sludge process may result in the production of dispersed floc particles and the loss of fine solids. Soaps are salts of large fatty acids, such as sodium stearate ($C_{17}H_{35}COO^{-}Na^{+}$). The cleaning action of soaps is due to their ability to emulsify or suspended water-insoluble organic compounds (fats and oils) in water and their ability to lower the surface tension of water.

Detergents have excellent cleaning properties. The key ingredient of detergents is the surfactant. The surfactant is a surface-active agent that acts to make water "wetter." By making the water "wetter," detergents become better cleaning agents. Surfactants concentrate at the interfaces of water with air, solids (dirt), and immiscible liquids (fats and oils).

Linear alkyl sulfonate (LAS) is an example of a commonly used surfactant (Figure 10.1). LAS is widely used in a variety of shampoos, cosmetics, cleaners, and laundry detergent formulations. Excessive surfactants or slowly degrading surfactants have several significant and undesired impacts on the activated sludge process (Table 10.1). Slowly degrading or persistent surfactants are known as cell bursting agents.

Soaps and detergents are commonly used as cleaning agents by many industries, commercial establishments, and households. Cell bursting agents often are used by food processing firms and pharmaceutical firms that need to thoroughly clean kettles or vats.

Soaps and detergents contain chemical compounds that produce an anionic charge when dissolved in wastewater. Because floc particles contain billions of bacteria that possess a net anionic charge, the floc particles possess a net anionic charge. When soaps and detergents come in contact with floc particles, they act as dispersing agents and the floc particle becomes weak. The weak particle releases fine solids to the bulk solution.

Like excessive turbulence, the presence of dispersing agents is highly undesired

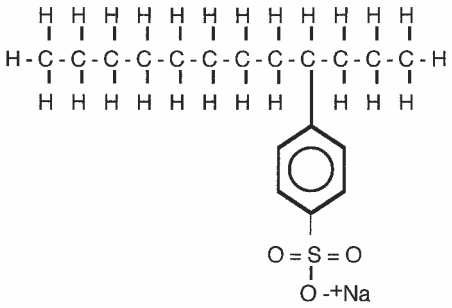

Figure 10.1 *LAS or linear alkyl sulfonate (*alpha*-benzene sulfonate). LAS contains a long and straight (linear) chain of carbon atoms and a (benzene) ring of carbon atoms. The sulfur group on the benzene ring is ionized.*

TABLE 10.1 Undesired Impacts of Surfactants on Activated Sludge Processes

Change in air bubble size in aeration tank due to decreased surface tension of wastewater
Deflocculation of colloids, dispersed cells, and particulate materials
Foam production and accumulation
Toxicity

TABLE 10.2 Indicators of the Presence of Surfactants

Increase in the amount of dispersed growth in the bulk solution
Presence of numerous small (<150 μm), spherical floc particles
Ruptured or burst bodies or body coverings of metazoa
Sluggishness or inactivity of ciliated protozoa and metazoa

in the activated sludge process. Surfactants cause an increase in TSS in the final effluent, possible permit violations for TSS, loss of treatment efficiency, and increased operational costs. Because surfactants change the surface tension of wastewater, they also produce billowy white foam and may change the size of air bubbles produced during aeration. Some surfactants also represent a toxicity concern.

INDICATORS OF THE PRESENCE OF SURFACTANTS

Although the presence and concentration of surfactants in wastewater can be determined through methylene blue testing, there are several microscopic indicators of the presence of surfactants in the activated sludge process (Table 10.2). Details of methylene blue testing for surfactants are presented in the latest edition of *Standard Methods*. These indicators include an increase in the amount of dispersed growth, the presence of small, and perhaps, spherical floc particles as the dominant size and shape of floc particles, ruptured or burst bodies or body cover-

ings of metazoa, and perhaps, sluggish activity or inactivity of ciliated protozoa and metazoa.

In a mature activated sludge process that is not adversely affected by surfactants, very little dispersed growth should be present in the bulk solution. The relative abundance rating for dispersed growth in this process should be "insignificant" or "0" on a scale of "0" to "2." However, if soaps or detergents adversely affect the activated sludge process, the amount of dispersed growth should increase considerably. The relative abundance rating for dispersed growth in an activated sludge process that is adversely affected by soaps or detergents should be "significant" or "1" or "excessive" or "2" on a scale of "0" to "2."

In a mature activated sludge process, medium (150–500 μm) and large (>500 μm) floc particles typically are the dominant size particles. Because of the presence of significant filamentous growth within the floc particles and extending into the bulk solution from the perimeter of the floc particles, these particles also should be irregular in shape. However, when soaps or detergents adversely affect the activated sludge process, the floc particles are continuously weakened and ruptured by the net negative charge of the dispersing agent.

As the floc particles are weakened and ruptured, numerous small floc particles are produced. Because the soaps or detergents are in solution and attack the entire perimeter of the floc particles, spherical floc particles may be produced (Figure 10.2). Small floc particles should be the dominant size in an activated sludge process that is adversely affected by dispersing agents.

Rotifers and free-living nematodes are commonly observed metazoa in the activated sludge process. These organisms have protective outer body coverings. The protective covering for the rotifer is the lorica (Figure 10.3), and the protective covering for the free-living nematode is the cuticle (Figure 10.4). The lorica and the cuticle are translucent.

The lorica is made of calcified materials and does not rupture in the presence of soaps or detergents. However, the cells beneath the lorica do rupture. Therefore,

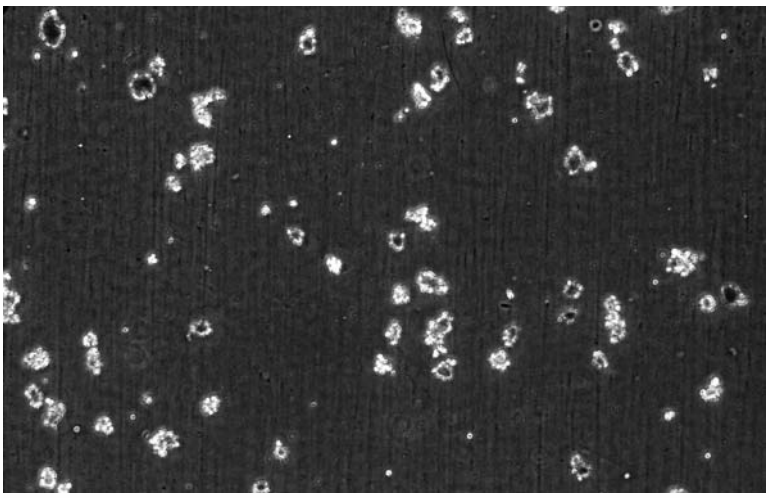

Figure 10.2 *Spherical floc particles produced through dispersion by surfactants.*

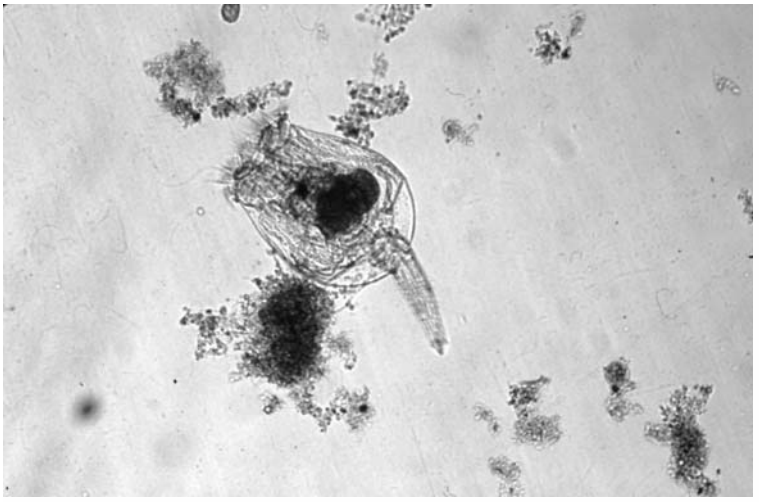

Figure 10.3 *Rotifer. The lorica is a translucent, protective covering that is found in many shapes. The presence of the lorica on a rotifer can be observed by its "horseshoe-shaped" edge immediately above its foot. Although the lorica is translucent, it is not ruptured or burst in the presence of surfactants.*

Figure 10.4 *Free-living nematode. The free-living nematode is a simply a tube within a tube that is within a tube. The free-living nematode is surrounded by protective and translucent cuticle. Under the cuticle is a longitudinal muscular system that surrounds a longitudinal digestive tract.*

during a microscopic analysis of activated sludge that contains dispersing agents, the outer edge or "horseshoe-shaped" image of the lorica and the loss of cells at the anterior end or mouth opening can be observed (Figure 10.5). The cuticle of the free-living nematode can be ruptured in the presence of soaps or detergents. When the cuticle is ruptured, the longitudinal muscular system and longitudinal digestive tract that are observed through the cuticle during microscopic analyses of activated

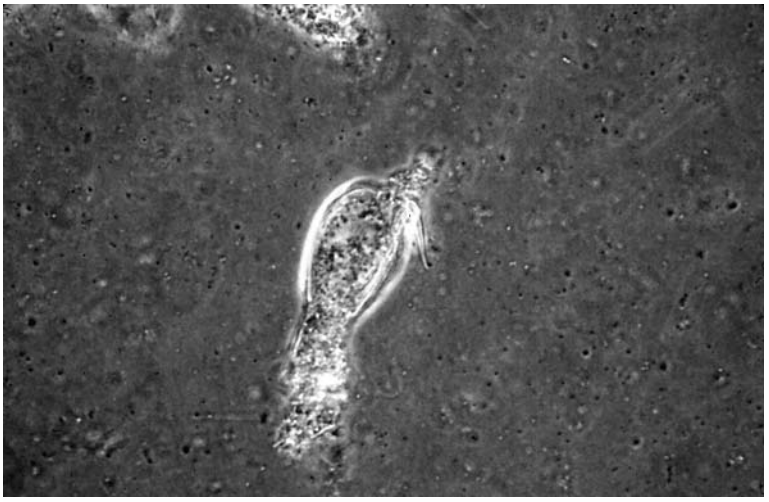

Figure 10.5 *Rotifer ruptured by surfactants. In the presence of excessive surfactants, the "soft" cells of the digestive system, gonads, and muscular system are ruptured but the lorica is not affected by the surfactants. The ruptured cells can be observed "spilling out" of the mouth opening of a burst rotifer, and the refracted light of the "horseshoe-shaped" edge of the lorica can be observed.*

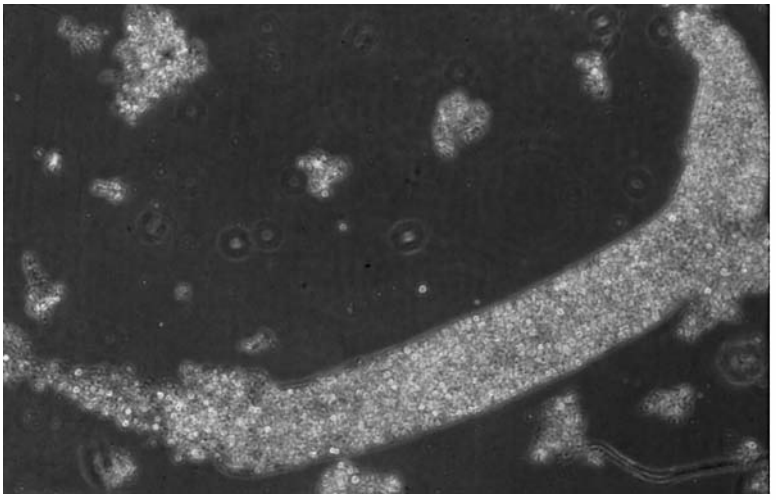

Figure 10.6 *Free-living nematode ruptured by surfactants. In the presence of excess surfactants, the "soft" cells of the cuticle are ruptured. Once the cuticle is burst, the muscular system and digestive system cannot be observed.*

sludge cannot be observed (Figure 10.6). Because surfactants do rupture the cells beneath the rotifer's lorica and the cells of the cuticle of free-living nematodes, the structural damage to these organisms serves as an indicator of the presence of soaps or detergents.

Toxicity caused by soaps or detergents can be observed in the sluggish activity or loss of activity in ciliated protozoa and metazoa. The loss of activity in ciliated

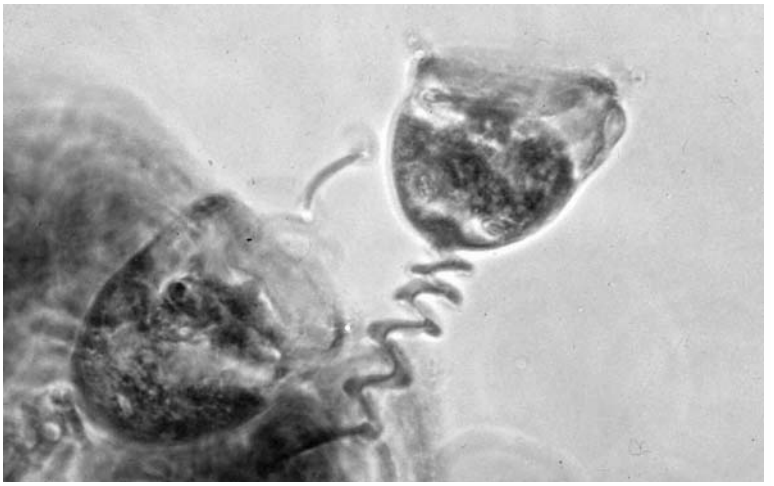

Figure 10.7 *Contractile filament in a stalk ciliated protozoa. Some stalk ciliated protozoa possess a contractile filament or myoneme in their stalk. This filament allows the protozoa to spring. The springing action is thought to create a water vortex that brings more bacteria into the mouth opening. Because some surfactants are toxic, the presence of excess surfactants may cause sluggish activity or loss of activity with respect to the springing action of the contractile filament.*

protozoa occurs not only as loss of locomotion in the bulk solution or on floc particles but also as loss of beating action of the cirri and springing action of the contractile filament in stalk ciliated protozoa (Figure 10.7).

CONTROL

Several measures can be used to reduce or prevent the adverse impacts of soaps or detergents on the activated sludge process. The industrial waste stream that contains the soaps or detergents should be identified. The Material Safety Data Sheets (MSDS) at suspected industries and commercial establishments should be reviewed to identify the suspect dispersing agent responsible for the loss of solids in the activated sludge process.

Dispersing agents that have been identified as causing adverse impacts should be regulated. Less aggressive soaps or detergents may be used or dispersing agents may be collected in a holding tank and pretreated with bioaugmentation products. The discharge of dispersing agents should be equalized and extended over a long period of time. Slug discharges should be prevented. If the activated sludge process has aeration tanks that are not used, consideration should be given to using these tanks and rotating aeration tanks "on-line" and "off-line" to dilute the incoming dispersing agents or to recover quickly from the adverse impacts of the dispersing agents.

11

Heavy Metals and Congealed Floc Particles

A large variety of metals enter most activated sludge processes. Many of these metals are referred to as "heavy" metals because of their adverse impacts on wastewater treatment plants (Table 11.1). Industrial wastewaters usually contain the largest variety and quantities of heavy metals. Because of the concerns over the toxicity of heavy metals, the effluent concentrations of several heavy metals are regulated at most activated sludge processes (Table 11.2). In the activated sludge process, heavy metals also are responsible for the loss of fine solids and the production of congealed floc particles.

Most metals that enter the activated sludge process are in solution as metal oxides or free ionic state species, for example, Cu^{2+} (copper) and Pb^{2+} (lead). The metals act as positively charged ions, or multivalent cations. Most metals are quickly removed from the bulk solution and are adsorbed to the negative or anionic sites of the fibrils on bacterial cells in the floc particle (Figure 11.1). Most metals are adsorbed to the bacterial cells within 30 minutes (Figure 11.2).

When metals are adsorbed to the surface of bacterial cells, several physical-biological and chemical-biological interactions occur. The presence of the metals on the bacterial cells adds weight to the floc particles. The metals also increase the density of the floc particles by pulling negatively charged bacterial cells more closely together. Increased weight and increased density result in more rapidly settling solids.

Some of the metals adsorbed to the surface of the bacterial cells are absorbed, that is, the metals enter the bacterial cells. Inside the bacterial cell, the metals attack cellular enzymes. This attack often occurs at the location of the thiol group (–SH) in some of the amino acids that make up the proteinaceous enzymes. It is this attack on enzymes that disrupts cellular activity and is responsible for toxicity.

Metals that are not absorbed by the bacterial cells remain on the fibrils. Because the metals occupy the negative sites of the fibrils, fine solids that normally would be

TABLE 11.1 Adverse Impacts of Heavy Metals in Wastewater Treatment Plants

Accumulation of metals in sludges that affect sludge disposal options and costs
Discharge of metals to the receiving stream
Loss of fine solids from the activated sludge process
Toxicity to nitrifying bacteria and loss of treatment efficiency for nBOD removal
Toxicity to organotrophic bacteria (methanogens) and loss of methane gas production in anaerobic digesters
Toxicity to organotrophic bacteria and loss of treatment efficiency for cBOD removal
Violation of metal discharge limits

TABLE 11.2 Commonly Regulated Heavy Metals in the Final Effluent of Wastewater Treatment Plants

Heavy Metal	Symbol
Aluminum	Al
Cadmium	Cd
Chromium	Cr
Copper	Cu
Iron	Fe
Lead	Pb
Nickel	Ni
Silver	Ag
Zinc	Zn

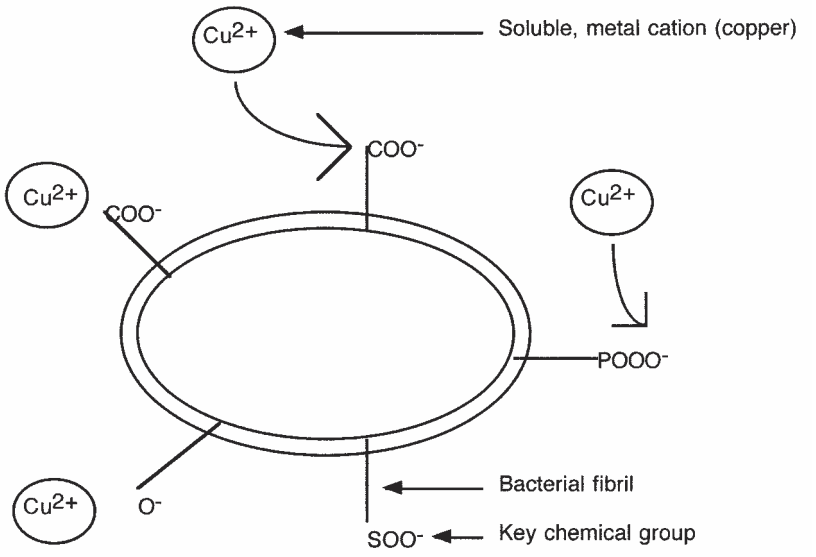

Figure 11.1 *Adsorption of heavy metals to bacterial fibrils. Metals in solution, such as copper (Cu^{2+}), act as positively charged ions or cations, whereas the ionized bacterial fibrils act as negative or anionic surfaces. These opposite charges strongly attract each other. As a result of this attraction, the soluble metals are quickly removed from the bulk solution and adsorbed to the bacterial fibrils.*

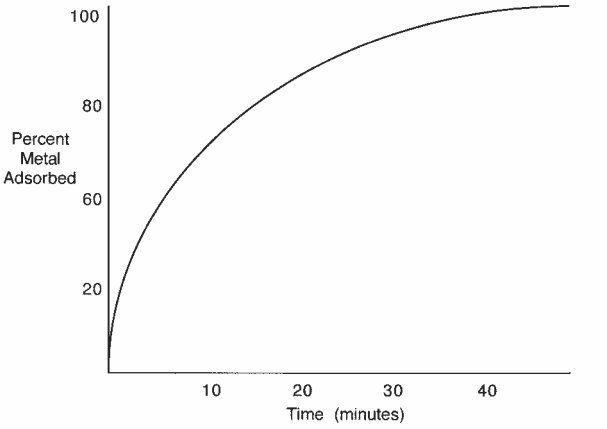

Figure 11.2 *Adsorption curve for the uptake of heavy metals. Heavy metals are removed quickly in the activated sludge process. Approximately 75% of the metals are removed within 10 minutes, and most of the remaining metals are removed within the next 20 minutes. Because heavy metals are so quickly removed, activated sludge processes that are susceptible to toxicity from heavy metal discharges must ensure proper pretreatment or regulation of metal dischargers.*

adsorbed to these sites remain in the bulk solution and are lost from the activated sludge process in the final effluent (Figure 11.3).

Heavy metal toxicity affects not only bacteria but also ciliated protozoa, rotifers, and free-living nematodes This attack results in decreased activity or loss of activity in these organisms and decreased numbers of these organisms as they are washed away in the final effluent.

Decreased activity and decreased numbers of ciliated protozoa, rotifers, and free-living nematodes also contribute to the loss of fine solids. The cropping action and coating action provided by these organisms is greatly reduced in the presence of heavy metal toxicity. With a smaller and less active population of higher life forms, a smaller number of dispersed cells are cropped and a smaller amount of fine solids is coated with biological secretions and adsorbed to floc particles.

INDICATORS OF HEAVY METAL TOXICITY

Although the analyses of soluble metal concentrations in the activated sludge can reveal the occurrence of toxic concentrations of heavy metals, there are several microscopic, biological, and chemical indictors of toxicity in the activated sludge process (Table 11.3). Microscopic indicators include an increase in the amount of dispersed growth, changes in density and shape of floc particles, changes in activity and number of ciliated protozoa, and a regression in the dominant protozoan groups. Biological indicators of toxicity include an increase in dissolved oxygen concentration in the aeration tank and a decrease in activated sludge specific oxygen uptake rate, or SOUR. Chemical indicators include increased mixed liquor effluent concentrations for ammonium ions, nitrite ions, and orthophosphate.

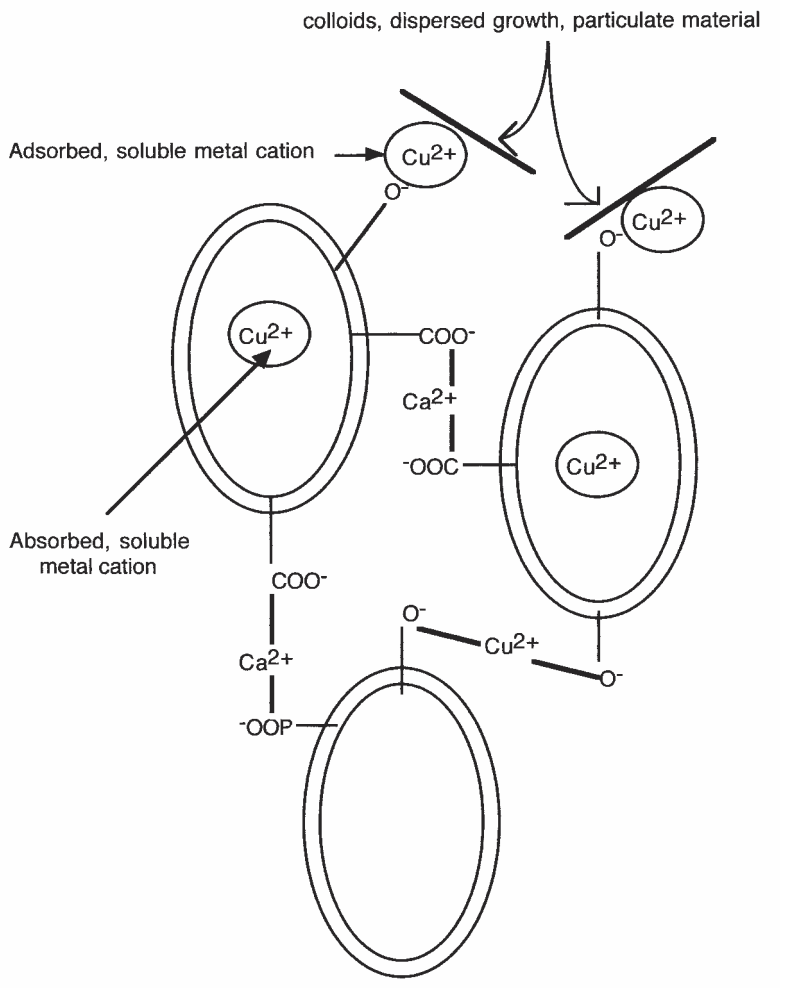

Figure 11.3 *Interference of heavy metals with the removal of fine solids. Because soluble heavy metals are so quickly adsorbed to the bacterial fibrils, fine solids cannot be removed in large quantities from the bulk solution. The adsorption of fine solids is hindered by the presence of heavy metals.*

TABLE 11.3 Indicators of Heavy Metal Toxicity

Type of Indicators	Indicators
Microscopic	Increase in the amount of dispersed growth
	Changes in density and shape of floc particles
	Changes in activity and number of ciliated protozoa
	Regression in the dominant protozoan groups
Biological	Increase in mixed liquor dissolved oxygen concentration
	Decrease in activated sludge SOUR
Chemical	Increase in mixed liquor effluent NH_4^+ concentration
	Increase in mixed liquor effluent NO_2^- concentration
	Increase in mixed liquor effluent PO_4^{2-} concentration

Heavy metals within the activated sludge process inhibit bacteria that remove cBOD and bacteria that nitrify or remove nBOD. During toxicity bacteria remove a smaller quantity of cBOD; therefore, less nitrogen and phosphorus are used or removed from the mixed liquor. Because less nitrogen and phosphorus are removed from the mixed liquor, higher than expected concentrations of ammonium ions and orthophosphate ions should be found in the mixed liquor effluent.

Because nitrifying bacteria are inhibited by heavy metals, nitrification becomes sluggish or is stopped. If nitrification is sluggish, the accumulation of nitrite ions occurs. Because the bacterium *Nitrosomonas*, which converts ammonium ions to nitrite ions, is more tolerant of heavy metal toxicity than the bacterium *Nitrobacter*, which converts nitrite ions to nitrate ions, the concentration of nitrite ions increases in the mixed liquor effluent and the concentration of nitrate ions decreases. If nitrification is stopped, ammonium ions are not oxidized in the aeration tank and they leave the tank in the mixed liquor effluent. Nitrite ions and nitrate ions are not produced if nitrification is stopped.

With decreased cBOD removal and nBOD removal in the aeration tank, less dissolved oxygen is consumed by bacterial activity. Because less dissolved oxygen is consumed, the dissolved oxygen concentration in the aeration tank should be higher. Because bacteria are less active in the presence of heavy metal toxicity, the SOUR should decrease (Table 11.4). The SOUR of an activated sludge process should be relatively consistent when sampled at the same location and same time each day. The SOUR should not change by more than ±2–3 mg/h/g VSS.

As more and more metals react with the floc particles, the particles become heavier and denser. If a relatively large quantity of heavy metals reacts with the floc particles, the floc particles may become oval in shape (Figure 11.4). This occurs because the negatively charged bacteria on the surface of the floc particle are pulled more closely together (Figure 11.5).

The change in density and shape of the floc particle can be observed through methylene blue staining (Appendix II). Under methylene blue staining, firm or dense floc particles in the presence of heavy metals are dark blue and should have no openings or holes (Figure 11.6). Weak floc particles stain light blue and possess large openings or holes (Figure 11.7). Often, individual bacteria or small groups of bacteria may be observed in weak floc particles.

In the presence of heavy metals, the activity and number of protozoa decrease. Because the beating action of the cilia becomes sluggish or stops, free-swimming ciliated protozoa cannot swim effectively against the hydraulic flow in the secondary clarifier and are not captured in large numbers in the RAS. These protozoa are

TABLE 11.4 Typical Ranges of SOURs for Various Modifications of the Activated Sludge Process at the Aeration Tank Effluent

Process Modification	SOUR Range
Conventional	8–20 mg/h/g VSS
Step Aeration	8–20 mg/h/g VSS
Extended Aeration	3–12 mg/h/g VSS
Contact Stabilization	5–15 mg/h/g VSS
	15–30 mg/h/g VSS

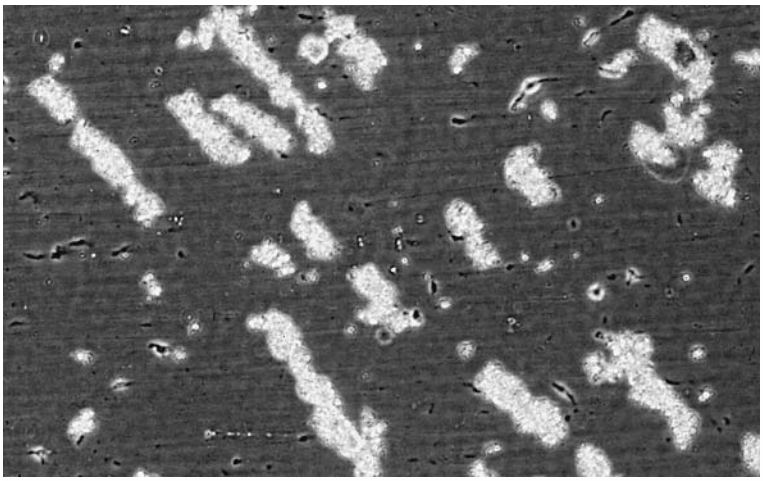

Figure 11.4 *Oval-shaped floc particles in the presence of heavy metals.*

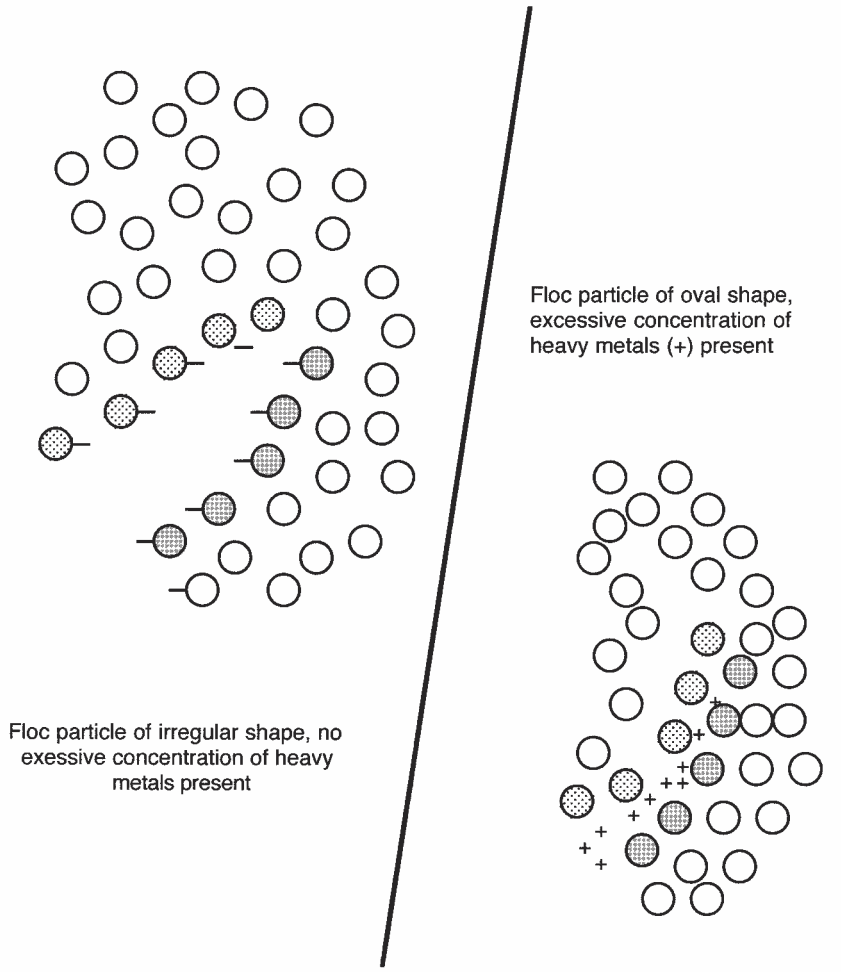

Figure 11.5 *Oval-shaped floc particles in the presence of heavy metals. In the presence of heavy metals the negatively charged bacteria and the negatively charged surface of the floc particles are pulled together more closely. This tight compaction of floc bacteria results in the production of very firm, oval-shaped floc particles.*

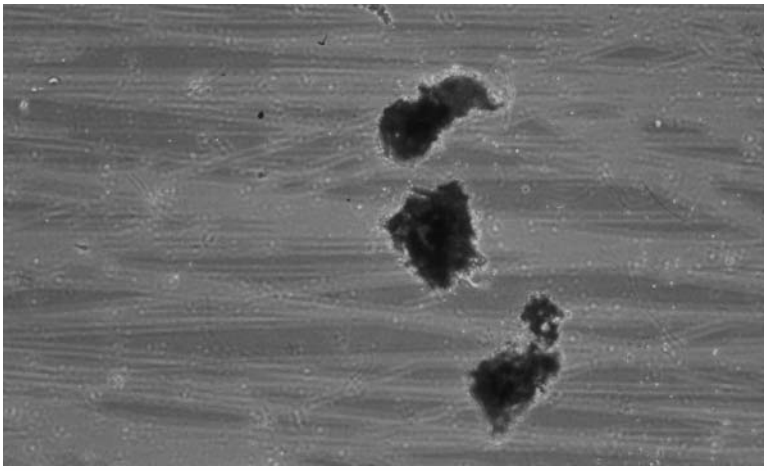

Figure 11.6 *Firm floc particles under methylene blue staining.*

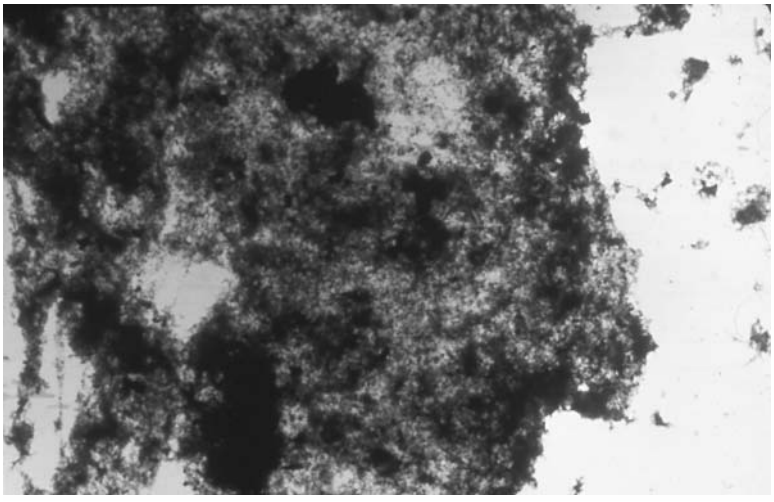

Figure 11.7 *Weak floc particles under methylene blue staining.*

lost in the secondary clarifier effluent. Therefore, the number of free-swimming ciliated protozoa in the aeration tank is reduced in the presence of heavy metal toxicity.

Crawling ciliated protozoa and stalk ciliated protozoa that are on or attached to floc particles are not lost in large numbers in the secondary clarifier effluent. Crawling and stalked protozoa are returned to the aeration tank in the RAS when floc particles settle in the secondary clarifier. However, sluggish activity or loss of activity can be observed in these organisms, especially the stalked protozoa.

In stalk ciliated protozoa, sluggish activity or loss of activity can be observed in the slow beating action or loss of beating action in the anterior cirri. Sluggish activity or loss of activity also can be observed in the sluggish springing action

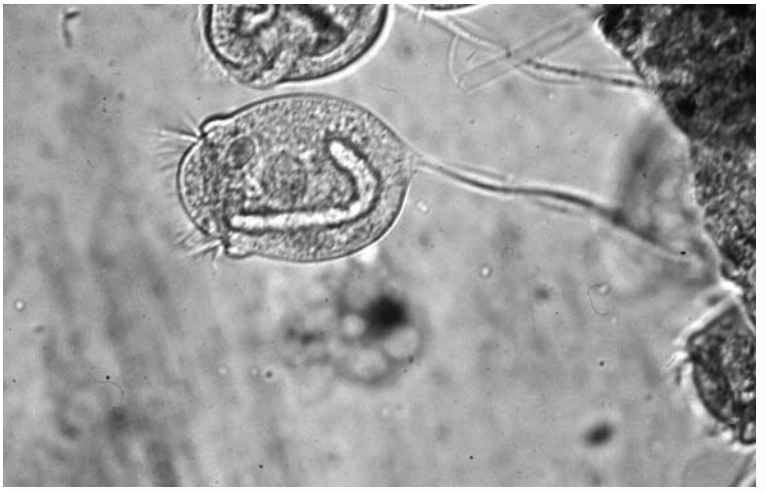

Figure 11.8 *Vorticella with a contractile filament in the slender posterior portion.*

Figure 11.9 *Opercularia without contractile filaments in the slender posterior portions.*

or loss of springing action of the contractile filament or myoneme of stalk ciliated protozoa.

The springing action of the myoneme produces a water vortex that draws bacteria into the mouth opening. Not all stalk ciliated protozoa have a contractile filament. The protozoa in the genus *Vorticella* do (Figure 11.8), whereas the protozoa in the genus *Opercularia* do not (Figure 11.9).

CONTROL

Several treatment measures may be used to reduce or prevent the adverse impacts of heavy metals on the activated sludge process. These measures include source control or reduction, increase in MLVSS, the use of bioaugmentation products, or the use of a biological holdfast system.

Waste streams that contain relatively high concentrations of heavy metals should be identified. These waste streams should then be regulated and monitored to ensure that only safe concentrations of heavy metals are present. No slug discharge of any heavy metal should be permitted.

MLVSS may be increased to reduce the adverse impacts of heavy metals. By increasing the MLVSS, the number of bacteria in the activated sludge process is increased. This increase in the number of bacteria lowers the ratio of the toxic mass of heavy metals to the bacterial mass. With a lower ratio, a larger number of bacteria are not affected by heavy metal toxicity.

Bioaugmentation products may be added to the activated sludge process to increase the number of bacteria or to provide bacteria that are more tolerant of the heavy metals. A biological holdfast system also may be used to increase the number of bacteria. A biological holdfast system consists of the placement of a fixed film growth medium in the aeration tank. Bacteria grow on the medium and are surrounded by bacteria (floc particles) in suspension. The suspended bacteria are discharged to the secondary clarifier, but the fixed film bacteria on the medium remain in the aeration tank. The use of a biological holdfast system permits an increase in the number of bacteria in the aeration tank without overloading the secondary clarifier.

12

Low Dissolved Oxygen Concentration

A low dissolved oxygen concentration in the aeration tank may be associated with several operational problems. Low dissolved oxygen may be associated with the undesired growth of filamentous organism (Table 12.1), loss of treatment efficiency for cBOD removal, loss of treatment efficiency for nBOD removal or nitrification, and the interruption of floc formation.

It is not the absence of dissolved oxygen that causes the interruption of floc formation, but the presence of a low dissolved oxygen concentration. This concentration hinders proper floc formation. Dissolved oxygen values responsible for the interruption of floc formation and loss of fine solids are <1.0 mg/l for ten or more consecutive hours.

A low dissolved oxygen level contributes to the interruption of floc formation and loss of solids through two significant and detrimental changes in the biomass. First, and more importantly, the floc bacteria are adversely affected. Second, the ciliated protozoan population is damaged.

IMPACT OF LOW DISSOLVED OXYGEN CONCENTRATION ON FLOC BACTERIA

When the dissolved oxygen concentration in the aeration tank is maintained at ≥1.0 mg/l, adequate numbers of bacterial fibrils and polyhydroxybutyrate (PHB) granules are produced to ensure proper floc formation (Figure 12.1). Bacterial fibrils are used to join together the bacterial cells in the floc particle and serve as active sites on which fine solids are adsorbed. Therefore, a dissolved oxygen concentration ≥1.0 mg/l promotes a firm and dense floc particle with the ability to adsorb many fine solids from the bulk solution.

When a low dissolved oxygen concentration occurs in the aeration tank, a decreased number of bacterial fibrils and PHB granules are produced (Figure 12.2).

TABLE 12.1 Filamentous Organisms That Proliferate under a Low Dissolved Oxygen Concentration

Haliscomenobacter hydrossis
Microthrix parvicella
Sphaerotilus natans
Type 1701

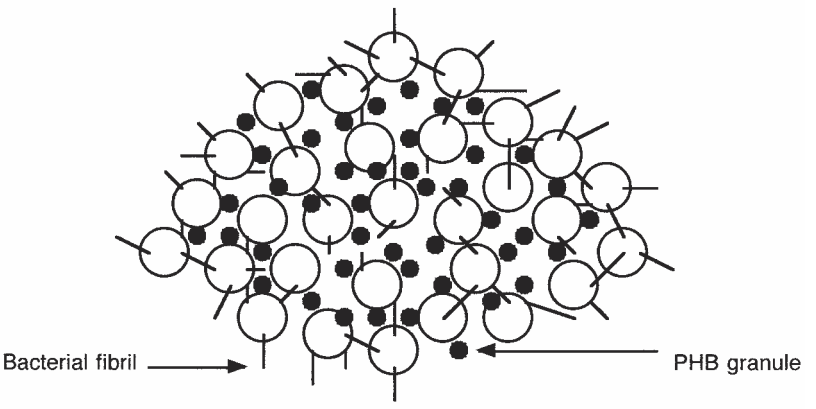

Figure 12.1 *Bacterial fibril and PHB production under an adequate dissolved oxygen level. Under an adequate dissolved oxygen level (≥1.0 mg/l), copious quantities of bacterial fibrils and PHB granules are produced. The PHB granules are located throughout the floc particle. The fibrils and PHB granules provide for the development of a firm, dense floc particle.*

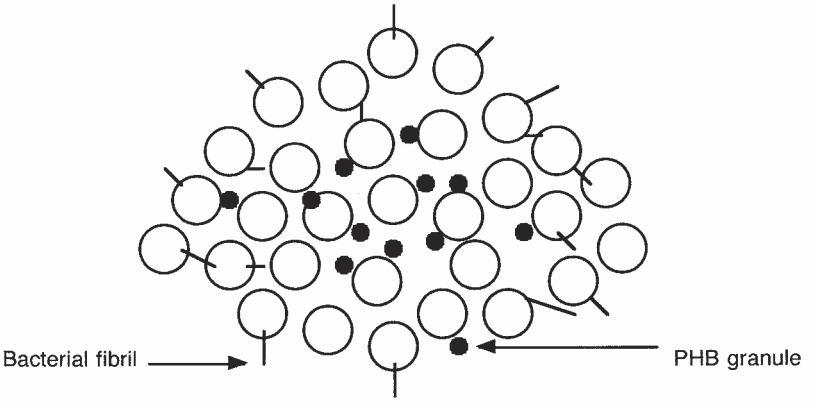

Figure 12.2 *Bacterial fibril and PHB production under low dissolved oxygen level. Under a low dissolved oxygen level (<1.0 mg/l) for 10 or more consecutive hours, a relatively small number of bacterial fibrils and PHB granules are produced. Most PHB granules are located in the core of the floc particle. The fibrils and PHB granules do not provide for the development of a firm, dense floc particle.*

Also, the PHB granules that are produced are found mostly at the core of the floc particle. With decreased fibril production, a smaller number of active sites are available for the adsorption of fine solids. The lack of adequate numbers of fibrils and PHB granules contributes to the production of weak and buoyant floc particles that may be easily sheared or may float out of the secondary clarifier. Fine solids that are not adsorbed to the floc particles also float out of the secondary clarifier.

IMPACT OF LOW DISSOLVED OXYGEN CONCENTRATION ON CILIATED PROTOZOA

When a low dissolved oxygen concentration exists in the aeration tank, ciliated protozoan activity becomes sluggish. Protozoa affected by a low dissolved oxygen concentration include free-swimming ciliates, crawling ciliates, and stalked ciliates. The effects of sluggish protozoan activity include reduced cropping action of dispersed bacteria and reduced coating action of fine solids. Reduced cropping action and reduced coating action result in an increased quantity of fine solids in the bulk solution.

A low dissolved oxygen concentration in the aeration tank also increases the generation time of ciliated protozoa. With an increase in generation time, the number of ciliated protozoa decreases in the activated sludge process. A decreased ciliated protozoan population also results in less cropping action and less coating action.

An abundant and active population of ciliated protozoa is capable of removing large quantities of fine solids from the bulk solution. Approximately 33% of mixed liquor influent colloids are removed from the bulk solution through ciliated protozoan activity. However, in the presence of a low dissolved oxygen concentration, large quantities of colloids as well as dispersed growth and particulate materials remain in the bulk solution because of the decrease in ciliated protozoan numbers and activity.

Decreased protozoan activity usually occurs 36 hours after the dissolved oxygen concentration decreases to a value <1.0 mg/l. Protozoa activity usually increases 12 hours after the dissolved oxygen concentration increases to 1.0 mg/l.

INDICATORS OF LOW DISSOLVED OXYGEN CONCENTRATION

Although in situ continuous monitoring of dissolved oxygen concentration is best for detecting the presence of a low dissolved oxygen concentration, there are several indicators of a low dissolved oxygen concentration (Table 12.2). These indicators may reveal the presence of stratification of dissolved oxygen or pockets of low dissolved oxygen in an aeration tank (Figure 12.3). These indicators also may reveal the presence of a poorly maintained or malfunctioning dissolved oxygen probe.

Indicators of low dissolved oxygen concentration include free-swimming *Vorticella*, sluggish *Aspidisca*, and the growth of low-dissolved-oxygen filamentous organisms. *Vorticella* are stalk ciliated protozoa that prefer to be attached to the surface of floc particles. However, under a low dissolved oxygen concentration

TABLE 12.2 Indicators of Low Dissolved Oxygen Concentration

Presence of free-swimming stalk ciliated protozoa
Presence of significant growth of filamentous organisms that proliferate under a low dissolved oxygen concentration
Sluggish activity of crawling ciliated protozoa
Weak floc particles as revealed through methylene blue staining

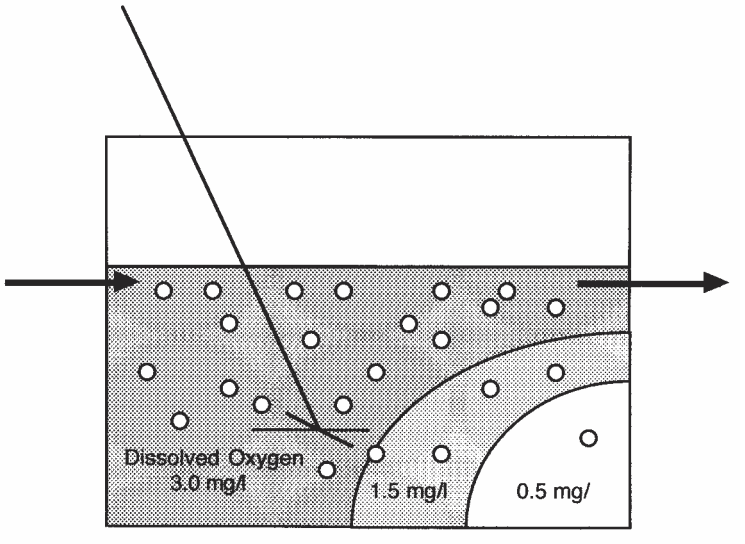

Figure 12.3 *Stratification of dissolved oxygen in an aeration tank.*

(<0.5 mg/l), *Vorticella* detach from the floc particle and swim freely in the bulk solution in search of a higher dissolved oxygen concentration (Figure 12.4). *Vorticella* swim freely by using their anterior cirri as a propeller and their posterior stalk as a rudder.

Aspidisca are crawling ciliates that usually swim or "crawl" on the surface of floc particles (Figure 12.5). The crawling motion is the result of the beating action of the cilia on the ventral surface of the protozoa, which is in contact with the floc particle. Under a low dissolved oxygen concentration, *Aspidisca* become sluggish.

The low dissolved oxygen concentration that contributes to the interruption of proper floc formation also may contribute to the undesired growth of low-dissolved-oxygen filamentous organisms. These organisms include *Haliscomenobacter hydrossis*, *Microthrix parvicella*, *Sphaerotilus natans*, and type 1701.

Floc particles in the presence of a low dissolved oxygen concentration become weak, with decreased production of fibrils and PHB granules. Bacteria in the floc particle are poorly flocculated, and the weak structure or compaction of the floc bacteria may be revealed through methylene blue staining. Weak floc particles show little blue staining, have openings or holes, and often have light blue areas in which individual bacterial cells may be observed.

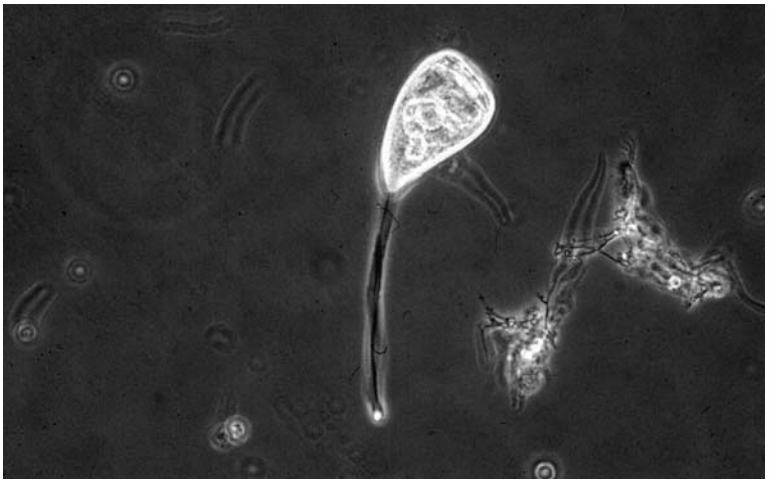

Figure 12.4 Vorticella *free-swimming in the bulk solution.*

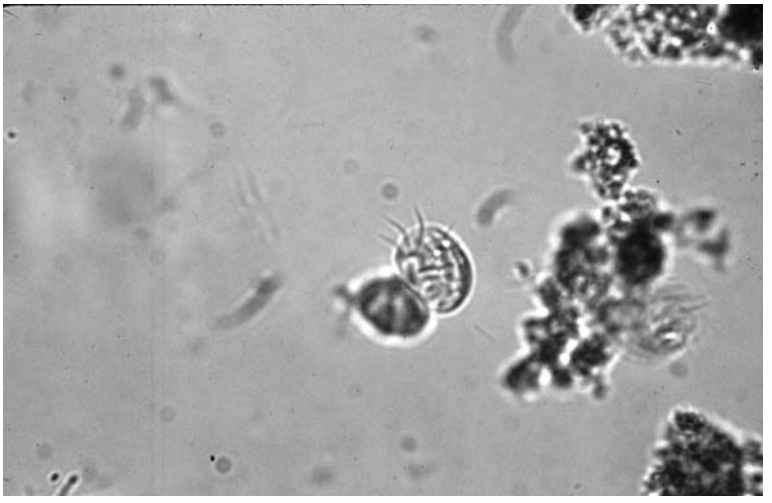

Figure 12.5 Aspidisca *crawling on the surface of a floc particle.*

CONTROL

The occurrence of a low dissolved oxygen concentration in an aeration tank may be corrected through several operational measures. First, increasing aeration capacity or making appropriate repairs to aeration equipment may increase the dissolved oxygen concentration. Second, influent waste streams should be monitored and regulated to prevent slug discharges of soluble cBOD and nitrogenous wastes. Wastewater discharges should be equalized. Third, if nitrification is occurring and is not required, then termination of nitrification should be considered. Finally, oxygen scavengers should be eliminated from waste streams.

Oxygen scavengers are used for corrosion control in cooling towers and may be found in industrial wastewaters. Commonly used oxygen scavengers include sodium sulfite ($NaSO_3$) and hydrazine (N_2H_4). Sulfite (SO_3^-) and hydrazine react with dissolved oxygen (O_2) before the dissolved oxygen can react with a metal surface and cause corrosion (Equations 12.1 and 12.2).

$$2SO_3^- + O_2 \rightarrow 2SO_4^{2-} \tag{12.1}$$

$$N_2H_4 + O_2 \rightarrow 2H_2O + N_2 \tag{12.2}$$

13

Young Sludge Age

When the activated sludge process is young, for example, <3 days of sludge age, many weak and buoyant floc particles are produced. These particles are easily sheared and often float out of the secondary clarifier. Many young floc particles are weak and buoyant because of the lack of adequate production of bacterial fibrils, PHB granules, and strong, flocculating polysaccharides and the lack of adequate filamentous growth.

Fine solids are lost from the activated sludge process through shearing of weak floc particles and the lack of an adequate population of ciliated protozoa and metazoa. At a young sludge age, the activated sludge process is an unfavorable environment for the growth of a large population of ciliated protozoa and metazoa. The environment is highly polluted with BOD and contains a relatively low dissolved oxygen concentration. Also, the number of bacteria that serve as a food source for the ciliated protozoa is relatively low. Small populations of bacteria and protozoa cannot support a large and active population of metazoa.

With a small population of ciliated protozoa and metazoa, insignificant cropping action and coating action occur in the activated sludge process. Cropping action refers to the consumption of dispersed bacteria, and coating action refers to the release of biological secretions by ciliated protozoa and metazoa that coat the surface of fine solids and allows these solids to be adsorbed to the surface of floc particles.

Although a young sludge age occurs during the start-up of an activated sludge process, there are other operational conditions that mimic a young sludge age (Table 13.1). These conditions include excess sludge wasting, hydraulic washout from excess I/I, recovery from toxicity, and a slug discharge of soluble cBOD.

CONTROL

To prevent settleability problems and loss of solids due to a young sludge age, sludge wasting should be stopped or the wasting rate should be reduced, to increase the

TABLE 13.1 Operational Conditions that Mimic a Young Sludge Age

Excess sludge wasting
Hydraulic washout
Recovery from toxicity
Slug discharge of soluble cBOD

sludge age of the activated sludge process. Also, conditions that mimic a young sludge age should be identified and corrected.

Significant sources of I/I can be identified through dye testing, smoke testing, and televising of sewer mains. Once identified, these sources of I/I should be repaired or disconnected from the sewer mains. Toxic wastes also should be identified as well as the dischargers of toxic wastes. Again, once identified, the discharge of toxic wastes should be terminated or regulated. Slug discharges of soluble cBOD should be identified and terminated. Significant quantities of soluble cBOD may be placed in holding tanks and discharged over as long a period of time as possible. The presence of large quantities of soluble cBOD results in rapid or logarithmic growth. This growth results in the production of young, weak, and buoyant floc particles.

14

Floc Particles Lost Through Sludge Aging

As they age, some floc particles float out of the secondary clarifier because of undesired floc particle structure. There are four floc particles that may be lost from the secondary clarifier with increasing sludge age (Table 14.1). These floc particles are pinpoint floc, straggler floc, ashing floc, and clumping floc.

PINPOINT FLOC

Pinpoint floc or pin floc is the first floc particle that develops within the activated sludge process. Pinpoint floc appears in the activated sludge process when the biomass is growing rapidly. Floc particles are light in color and spherical in shape, and they lack filamentous growth.

Some floc particles may be buoyant and weak because of inadequate production of bacterial fibrils, polysaccharides, and PHB granules and lack of adequate filamentous growth. Pinpoint floc usually appears at the effluent end of the secondary clarifier. The loss of pinpoint floc can be corrected by reducing the WAS rate. The reduction in the WAS rate produces an increase in the sludge age of the activated sludge process.

Dense floc particles settle rapidly during a settleability test, whereas buoyant floc particles settle slowly. A settleability test of pinpoint floc produces a low sludge volume index (SVI) (Appendix I) and a cloudy or turbid supernatant.

STRAGGLER FLOC

Straggler floc develops after pinpoint floc and appears in the activated sludge process when a reduction in rate of growth of the biomass has occurred. Straggler floc is dark in color and irregular in shape, and it has filamentous growth.

TABLE 14.1 Floc Particles Lost Through Sludge Aging

Floc Particle	Growth	Description	Settleability Test Results
Pinpoint	Rapid	Floc particles are light in color and spherical in shape and lack filamentous organisms.	Low SVI and cloudy or turbid supernatant
Straggler	Moderate	Floc particles are dark in color and irregular in shape and possess filamentous organisms. Some filaments extend into the bulk solution.	High SVI and clear supernatant
Ashing	Slow	Floc particles are dark in color, irregular in shape, and large in size and possess significant filamentous organisms and biological secretions.	High SVI and clear supernatant
Clumping	Slow	Floc particles are dark in color, irregular in shape, and large in size and possess significant filamentous organisms, biological secretions, and entrapped gas bubbles.	High SVI, clear supernatant, and floating solids with attached and entrapped gas bubbles

Because some straggler floc has filamentous growth that extends into the bulk solution and interferes with the compaction of settling solids, straggler floc may be lost from the secondary clarifier.

Straggler floc may be found on the entire surface of the secondary clarifier. The loss of straggler floc from the secondary clarifier can be corrected by increasing the WAS rate. An increase in the WAS rate produces a decrease in the sludge age of the activated sludge process. Straggler floc also can be corrected by controlling the growth of filamentous organisms.

ASHING FLOC

Ashing may occur in the secondary clarifier with straggler floc. Ashing floc develops after straggler floc and appears in the activated sludge process when a reduction in rate of growth of the biomass has occurred. Ashing floc is dark in color and irregular in shape, and it has significant filamentous growth. Ashing also is associated with the accumulation of biological secretions by an aging bacterial population.

Ashing on the surface of the secondary clarifier appears as many large, dark, and irregularly shaped floc particles. Ashing is found throughout the entire surface of the secondary clarifier—as if someone scattered ashes over the surface of the secondary clarifier. Ashing can be corrected by increasing the WAS rate. An increase in the WAS rate produces a decrease in the sludge age of the activated sludge process. Ashing floc also can be corrected by controlling the growth of filamentous organisms.

CLUMPING FLOC

Clumping floc is the last of the floc particles to be developed through sludge aging. Clumping is the rising of large “clumps” of settled solids from the floor of the

secondary clarifier. Clumping occurs because denitrification is occurring in the secondary clarifier.

With increasing sludge age, large numbers of nitrifying bacteria in the aeration tank produce nitrate ions through nitrification. When these ions undergo denitrification in the secondary clarifier, they release molecular nitrogen (N_2), nitrous oxide (N_2O), and carbon dioxide (CO_2) that accumulate in the floc particles and cause buoyant or rising sludge. The sludge rises to the surface of the secondary clarifier as large clumps of dark solids.

Clumping may be associated with severe ashing and activated sludge processes with large secondary clarifiers and low RAS rates. Clumping may be corrected by increasing the RAS rate, increasing the WAS rate, and controlling nitrification and denitrification.

AGING FLOC PARTICLES, FOAM, PROTOZOA, FILAMENTOUS ORGANISMS, AND METAZOA

The development of floc particles in the activated sludge process can be correlated with changes in foam produced and accumulated in the aeration tank, the dominant protozoan groups, the absence or presence of filamentous organisms, and the absence or presence of a large, active metazoan population (Figure 14.1). Characteristics of floc particles can be described as they appear in a wet mount of mixed liquor as viewed through a microscopic examination or on the surface of the secondary clarifier.

During the start-up of an activated sludge process, the bacterial population is young and relatively small. Because of the young age of the bacterial population, floc formation has not yet started. The population sizes of the bacterial and protozoan communities are relatively small. The small sizes of these communities provide poor treatment efficiency.

A microscopic examination of the activated sludge reveals the absence of floc particles and filamentous organisms and an excessive amount of dispersed growth. Because of the relatively high BOD and low dissolved oxygen concentration, amoebae and flagellates are the dominant protozoan groups.

With a relatively small bacterial population, dispersing agents are not degraded in the aeration tank and billowy white foam is produced. This foam accumulates on the surface of the aeration tank. Because poor treatment efficiency exists in the activated sludge process, a copious quantity of fine solids is found in the supernatant of the secondary clarifier.

With increasing sludge age, floc formation begins. First, an increase in number of bacteria occurs. This increase is quickly accompanied by an increase in the number of free-swimming ciliated protozoa. Together, the bacteria and the protozoa provide increased treatment efficiency. Second, floc particles appear. Although free-swimming ciliated protozoa are the dominant protozoan group, crawling ciliated protozoa can be found on the surface of the floc particles.

A microscopic examination of the activated sludge reveals the absence of filamentous organisms and the presence of lightly colored and spherical floc particles. Most floc particles are small in size (<150 μm). These small, spherical floc particles are referred to as pinpoint floc. A reduced quantity of dispersed growth can be found

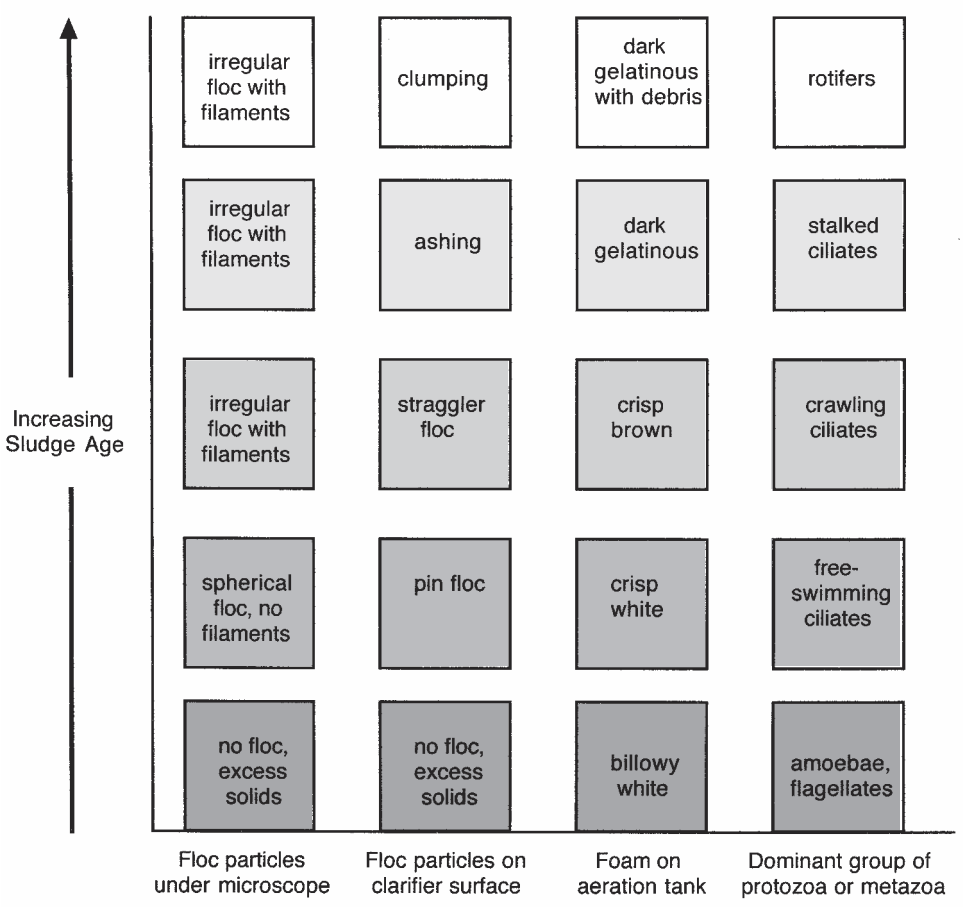

Figure 14.1 *Aging floc particles, foam, protozoa, filamentous organisms, and metazoa. With increasing sludge age, several significant changes occur in the development of the floc particle, foam, dominant protozoa groups, the presence of filamentous organisms, and the appearance of metazoa. Changes in the development of the floc particle can be observed through microscopic examination or can be observed in the type of floc particles that appear on the surface of the secondary clarifier. Changes in foam can be observed with respect to its texture and color, and the dominant protozoan group and appearance of large numbers of metazoa can be correlated with increasing treatment efficiency.*

in the bulk solution because of the coating action and cropping action provided by the protozoan community.

With increased treatment efficiency, dispersing agents are degraded and crisp white foam appears on the surface of the aeration tank. Because of the increasing treatment efficiency that is provided through bacterial activity and protozoan cropping and coating action, a significant reduction in the quantity of fine solids can be found in the supernatant of the secondary clarifier. Pinpoint floc particles may be observed on the surface of the secondary clarifier.

As the sludge age of the activated sludge process continues to increase, significant filamentous growth occurs. The growth of filamentous organisms provides for

an increase in the size of floc particles and a change in the shape of the floc particles to irregular as the floc bacteria grow along the lengths of the filamentous organisms. With more bacteria present in the activated sludge process, more treatment efficiency occurs. The resulting decrease in BOD and increase in dissolved oxygen concentration provide for the rapid proliferation of crawling ciliated protozoa.

A microscopic examination of the activated sludge reveals the presence of filamentous organisms extending into the bulk solution from the perimeter of dark and irregularly shaped floc particles. Most floc particles are medium in size (150–500 μm). These particles are known as straggler floc when they appear on the surface of the secondary clarifier. An insignificant quantity of dispersed growth can be found in the bulk solution, and a relatively large number of crawling ciliated protozoa can be found on the surface of floc particles. Stalk ciliated protozoa also may be observed in relatively large numbers.

With increasing sludge age, brown foam is produced and accumulated on the surface of the aeration tank. Foam production is caused by the buildup of biological secretions in the aging floc particle. An insignificant quantity of dispersed growth also should be observed in the supernatant of the secondary clarifier.

As sludge age continues to increase, so does treatment efficiency. Filamentous organisms continue to grow in length and number, and the floc particles grow even larger. Floc particles are large in size (>500 μm), dark in color, perhaps golden brown, and irregular in shape.

A microscopic examination of the activated sludge reveals the presence of numerous filamentous organisms extending into the bulk solution from the perimeter of large, irregular, and golden brown floc particles. Numerous stalk ciliated protozoa should be present on the surface of floc particles. An occasional rotifer or free-living nematode may be observed in the bulk solution or on the floc particles. The bulk solution should contain very little, if any, dispersed growth.

Floc particles or ashing may be observed on the surface of the secondary clarifier if filamentous organisms are present in undesired numbers. Because of the relatively old sludge age of the activated sludge process, some foam-producing filamentous organisms may be present in the floc particles. These organisms release lipids that accumulate in the floc particle and provide for the production and accumulation of gelatinous or viscous dark brown foam. Very little dispersed growth should be found in the supernatant of the secondary clarifier.

Finally, at a very old sludge age, nitrification and denitrification may occur in the activated sludge process. At an old sludge age, adequate numbers of nitrifying bacteria produce nitrate ions in the aeration tank that are used by denitrifying bacteria in the secondary clarifier to degrade soluble cBOD. Gases released through denitrification collect in the floc particles or solids. The gases produce rising solids or clumping floc particles in the secondary clarifier.

A microscopic examination of the activated sludge reveals the presence of numerous filamentous organisms extending into the bulk solution from the perimeter of large, irregular, and golden brown floc particles. Numerous, active stalk ciliated protozoa again should be attached to the surface of floc particles. An active population of rotifers and free-living nematodes may be observed in the bulk solution or on the floc particles. The bulk solution should contain very little, if any, dispersed growth.

If the field of view of a wet mount is not moved on the stage of the microscope,

and the light is left on, the capture of a bubble of gas produced through denitrification may be observed. As the light warms the wet mount, the bacteria become active in the wet mount and rapidly remove any residual dissolved oxygen to degrade soluble cBOD in the wet mount. When the dissolved oxygen concentration is exhausted, the bacteria use the nitrate ions within the wet mount to degrade soluble cBOD. Some of the gases released during denitrification become entrapped in the filamentous organisms and floc particles in the wet mount.

The foam on the surface of the aeration tank remains dark and gelatinous but contains much particulate material. Particulate material removed from the bulk solution and adsorbed to floc particles becomes part of the foam as the floc particles move into the foam. This material gives the foam a gritty texture.

15

Slug Discharge of Soluble cBOD

A slug discharge of soluble cBOD is often described as the presence of two to three times as much soluble cBOD than expected in a 2- to 3-hour period of time. If adequate dissolved oxygen and nutrients are present in the aeration tank, the bacterial population rapidly degrades soluble cBOD. This degradation of a slug discharge of soluble cBOD results in logarithmic or young bacterial growth. It is rapid or young growth of bacteria that results in settleability problems and loss of solids.

A slug discharge of soluble cBOD changes the characteristics of a floc particle from old growth to young growth (Table 15.1). Rapidly growing, young bacteria do not agglutinate or flocculate as firmly as slowly growing, old bacteria. This difference in flocculating strength between young bacteria and old bacteria can be observed with a safranin-stained smear (Figure 15.1) of an activated sludge sample that has experienced a slug discharge of soluble cBOD (Appendix II).

Because the rapidly growing, young bacterial cells flocculate poorly, the resulting floc particles are buoyant and weak. These particles settle poorly and are sheared easily. Because aeration rates and RAS rates often are increased during a slug discharge, the increased turbulence levels in the aeration tank and RAS pumps produce many fine solids as the floc particles are sheared.

An additional factor that renders the floc particles weak or poorly agglutinated during a slug discharge of soluble cBOD is the lack of PHB production. When PHB is deposited outside bacterial cells, it serves two important floc formation roles: first, it helps to anchor bacterial cells together, and second, it helps to anchor particulate materials to the surface of floc particles. PHB granules can be observed through PHB staining of a smear of activated sludge (Appendix II).

During old growth, PHB production and deposition can keep up with bacterial growth. PHB granules are found in adequate amounts throughout the floc particle (Figure 15.2). In old growth sludge, PHB granules contribute to the production of firm and dense floc particles.

TABLE 15.1 Floc-Forming Characteristics of Young and Old Bacterial Growth

Characteristic	Young Bacterial Growth	Old Bacterial Growth
Fibril production	Few	Many
Fibril charge	Low	High
Polysaccharide production	High	Low
Polysaccharide strength	Weak	Strong
PHB production	Low	High
PHB location	Core of particle	Core and perimeter of particle

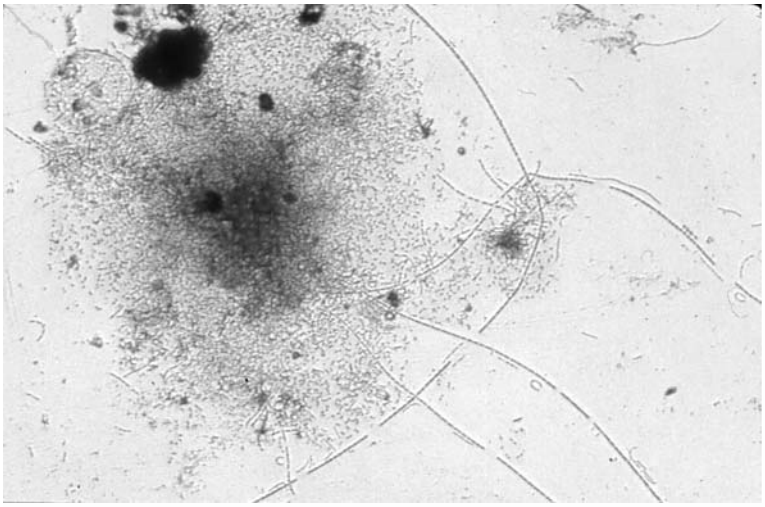

Figure 15.1 *Difference in flocculating strength of young and old bacterial growth. In this safranin-stained smear of a floc particle from an activated sludge process that has experienced a slug discharge of soluble cBOD, the difference in flocculating strength of young and old bacterial growth can be observed. The rapidly growing young bacterial cells are poorly flocculated at the perimeter of the floc particle, whereas the slow growing old bacterial cells are strongly flocculated at the core of the floc particle.*

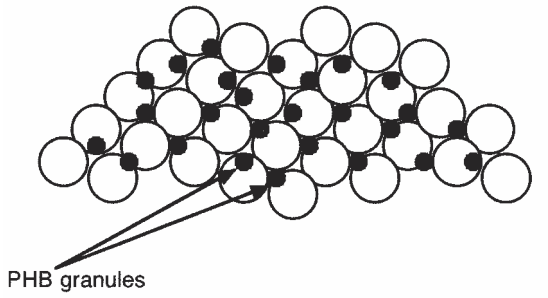

Figure 15.2 *PHB production and deposition in an old floc particle. During old growth, PHB granules are produced in adequate numbers and are deposited throughout the floc particle. Adequate PHB production and deposition in an old floc particle provides for firm, dense floc particles.*

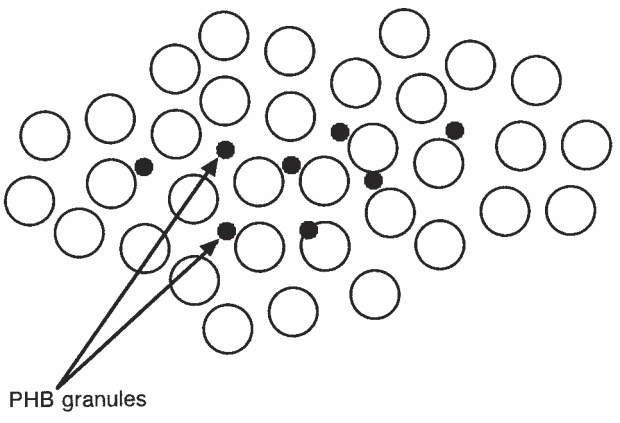

Figure 15.3 *PHB production and deposition in a young floc particle. During young growth, PHB granules are not produced in adequate numbers and are deposited mostly in the core of the floc particle. The lack of adequate numbers and deposition of PHB in the core of the floc particle is due to the rapid increase in numbers of young bacterial cells. Lack of PHB production and deposition in a young floc particle provides for weak, buoyant floc particles.*

During young growth, PHB production and deposition cannot keep up with bacterial growth, and PHB granules are not found in adequate amounts throughout the floc particle (Figure 15.3). In young growth sludge, lack of PHB deposition in the perimeter of the floc particle contributes to the growth of weak and buoyant floc particles. Because PHB granules help to anchor particulate materials to the perimeter of floc particles, particulate materials on the perimeter of the floc particles are easily sheared and lost to the bulk solution during a slug discharge of soluble cBOD.

CONTROL

To prevent the production of weak and buoyant floc particles by a slug discharge of soluble cBOD, it is necessary to identify potential sources of slug discharges of soluble cBOD. Once these dischargers have been identified, their waste streams should be monitored and regulated. The use of holding tanks for flow equalization, the discharge of wastewater over as long a period of time as possible, and the pretreatment of soluble cBOD are recommended.

16

Viscous Bulking or Zoogloeal Growth

The rapid, undesired growth of floc-forming bacteria is known as viscous bulking or Zoogloeal growth. This growth results in the production of weak and buoyant floc particles. Weak floc particles may be easily sheared, resulting in the loss of fine solids, and buoyant floc particles compact poorly in secondary clarifier. Zoogloeal growth may be associated with the production and accumulation of white, billowy foam on the surface of the aeration tank. Zoogloeal growth also may appear as a slimy white or grayish-white film on the weirs and walls of the secondary clarifier.

The term "Zoogloeal" was obtained from the genus name of the bacterium *Zoogloea ramigera*. This bacterium was one of the first floc-forming bacteria that were identified as bulking organisms in the activated sludge process. There are several specific operational conditions associated with the rapid and undesired growth of floc-forming bacteria (Table 16.1). These conditions include high and low F/M, high MCRT, long HRT, nutrient deficiency, and the presence of readily degradable cBOD.

Many of the floc-forming bacteria including *Zoogloea ramigera* are strict aerobic, rod-shaped, Gram-negative cells. These organisms produce large quantities of gelatinous, exocellular polysaccharides during rapid growth. The polysaccharides are insoluble in wastewater, less dense than wastewater, and water retentive. If the polysaccharides entrap air bubbles and gases, foam production may occur. Foam typical of viscous bulking is billowy white.

There are two patterns of Zoogloeal growth. These patterns are "fingered" or dendritic projections (Figure 16.1) and "amorphous" or globular (Figure 16.2). Amorphous Zoogloeal growth has no specific form.

Zoogloeal growth can be detected with a microscopic scan of a wet mount of activated sludge. Zoogloeal growth in floc particles can be observed at ×100 total magnification, and its presence may be more easily observed with methylene blue staining.

TABLE 16.1 Operational Conditions Associated with Zoogloeal Growth

High or low F/M
High MCRT
Long HRT
Nutrient deficiency
Presence of readily degradable cBOD

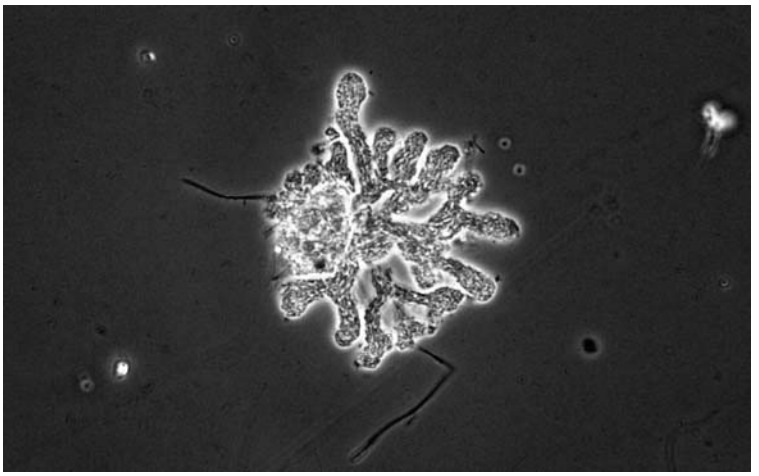

Figure 16.1 *"Fingered" Zoogloeal growth.*

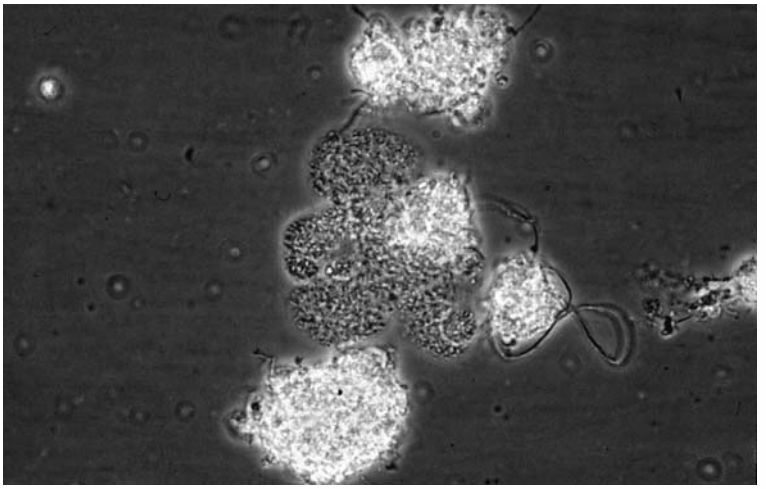

Figure 16.2 *"Amorphous" Zoogloeal growth.*

CONTROL

Viscous bulking may be corrected with several operational measures. These measures include adjusting the F/M, MCRT, and HRT, the use of anoxic periods or zones, and the addition of chemicals. Although chlorination can destroy floc-forming bacteria, the addition of chlorine may easily disperse the weak Zoogloeal growth, resulting in the loss of fine solids from the secondary clarifier.

Because many of the rapidly growing floc-forming bacteria are strict aerobes, the use of anoxic periods or zones of 1- to 2-hours duration may control the growth of these bacteria. The polysaccharides secreted by the floc-forming bacteria have a large and highly charged surface. The net surface charge of the polysaccharides may be anionic or cationic. Therefore, the addition of an appropriately charged polymer to the secondary clarifier influent may help to capture fine solids and improve solids settleability.

17

Increase in Percent MLVSS

An increase in the volatile content of the biomass or percent MLVSS contributes to an undesirable settling of floc particles or solids. An increase in percent MLVSS may result from physical or biological changes in the floc particles.

PHYSICAL CHANGES

The physical adsorption of fats, oils, and grease (FOG) by floc particles results in an increase in percent MLVSS. FOG enters a wastewater treatment plant from industrial, commercial, and domestic sources. Fats, oils, and grease that are not removed in the primary clarifier enter the activated sludge process.

Fats are a group of naturally occurring substances consisting of the glycerides of higher fatty acids, for example, palmitic acid, stearic acid, and oleic acid (Figure 17.1). Oils are a group of neutral liquids. There are two important groups of oils that are commonly discharged to activated sludge processes. These groups are fixed or fatty oils and mineral oils. Fixed oils are derived from animal and vegetable sources, whereas mineral oils are derived from a variety of hydrocarbons including petroleum and coal. Grease is a semisolid form of lubricant and is composed of emulsified mineral lubricating oil and soda or lime soap.

Fats and oils are found in commercial and domestic wastewaters in butter, lard, margarine, and vegetable fats and oils. Fats also are found in meats, nuts, and seeds. Fats and oils are relatively stable and are not easily degraded by bacteria. Mineral oils and grease are found in commercial and industrial wastewaters from garages, shops, and industries. Mineral oils also enter the sewer system in the form of road oils if catch basins are collected to the sewer system. Mineral oils easily coat floc particles and interfere with bacterial activity and floc particle structure.

In the activated sludge process, fats, oils, and grease, especially mineral oils, easily coat floc particles and interfere with bacterial activity and floc particle structure

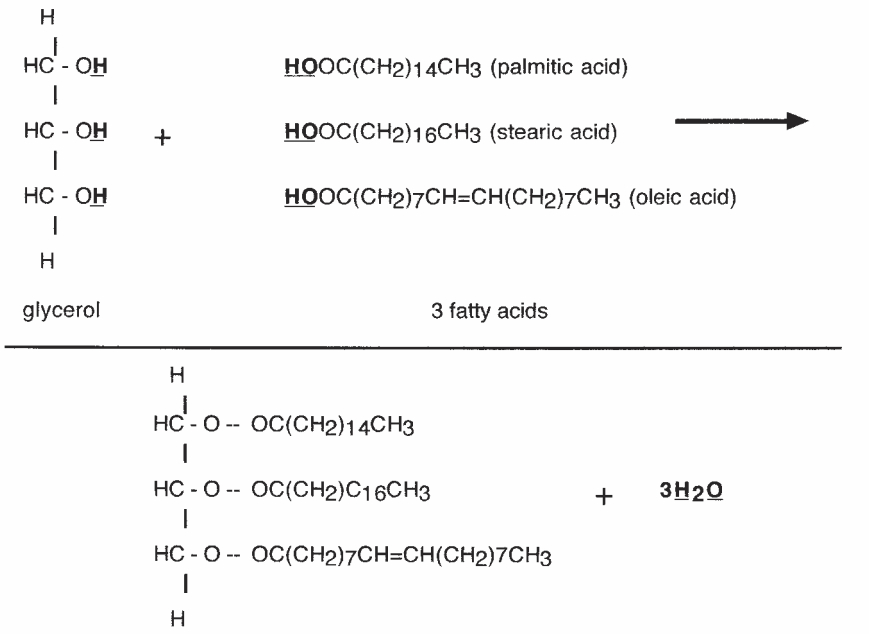

Figure 17.1 *Composition of a fat. When glycerol combines with three fatty acids, fat is produced. There are a variety of fatty acids that may combine with glycerol. A hydrogen atom from each hydroxyl group (–OH) from the glycerol and a hydroxyl group from each fatty acid combine to form three molecules of water.*

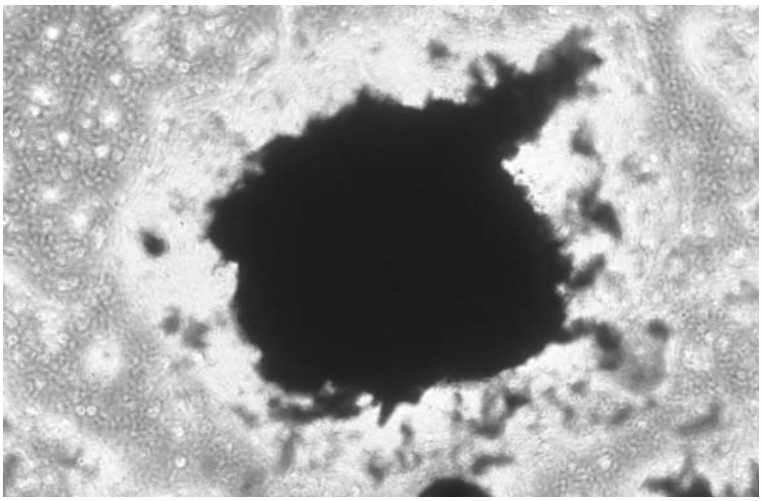

Figure 17.2 *Oil coating a floc particle.*

(Figure 17.2). Some of the fats, oils, and grease that are chemically similar in structure to the lipids in bacterial cell walls are absorbed in the cell walls.

Fats, oils, and grease on the surface of the floc particles not only increase the percent MLVSS but also cover the opening of the channels in the floc particles

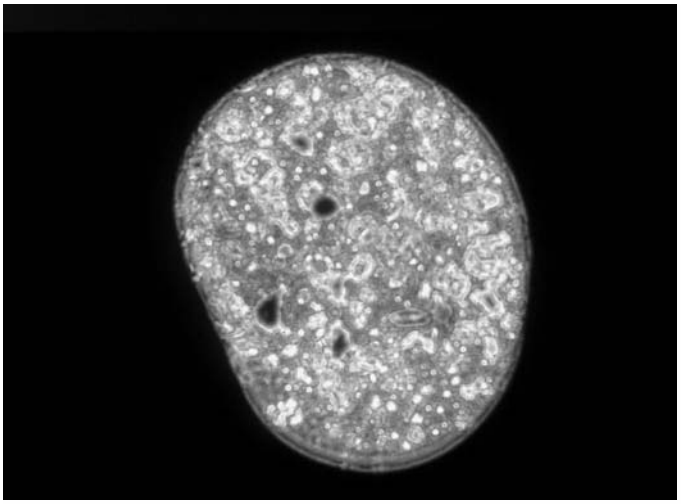

Figure 17.3 *Oil surrounding floc particles and dispersed growth. When mixed with a drop of India ink, the aqueous bulk solution of a mixed liquor wet mount becomes black. However, the carbon black particles in the India ink cannot penetrate into the oil, and the oil remains clear. Within the oil are many small floc particles and much dispersed growth.*

through which water flows as the floc particles settle in the secondary clarifier. The presence of FOG over the opening of the channels hinders the movement of water through the floc particles and entraps air bubbles and gases. These conditions adversely affect solids settleability and contribute to foam production and accumulation. Foam typical of the presence of FOG on floc particles is viscous dark brown or black.

Small floc particles and dispersed growth may be captured in droplets of FOG (Figure 17.3). When these droplets float out of the secondary clarifier, so do the floc particles and dispersed growth.

Most fats, oils, and grease degrade slowly or do not degrade in the activated sludge process. Fats, oils, and grease that accumulate in floc particles and are transferred to an anaerobic digester may contribute to a digester foaming problem or may cause toxicity in methane-forming bacteria.

CONTROL

To prevent an increase in percent MLVSS caused by FOG, significant dischargers of FOG should be identified and the FOG should be pretreated or removed. FOG may be removed through the use of an appropriate grease trap or grease separator. FOG removed by a grease trap should be hauled away and disposed of at an appropriate landfill. There are numerous benefits that may be obtained for a wastewater treatment system by reducing the quantity of FOG discharged to the sewers (Table 17.1).

Bioaugmentation products also may be used to control FOG. Bacteria with the enzymatic ability to degrade FOG, especially those with the enzyme lipase, may be

TABLE 17.1 Benefits that May Be Obtained by a Reduction in the Quantity of FOG Discharged to the Sewers

Reduction in Discharge of FOG to	Benefit
Sewer system	Decreased interruptions of sewer service
	Decreased malodor problems
	Decreased maintenance of lift stations
Wastewater treatment plant	Decreased foam production in aeration tanks
	Decreased organic loading
	Decreased risk of toxicity to anaerobic digesters
	Decreased scumming of FOG from primary clarifiers
	Decreased sludge production
	Improved settleability of floc particles
	Improved treatment efficiency
	Reduction in the growth of foam-producing filamentous organisms, such as Nocardioforms and *Microthrix parvicella*

used on-site at the source of discharge of FOG or added to the sewers, lift stations, and headworks of the treatment plant or the aeration tanks.

BIOLOGICAL CHANGES

There are two significant biological changes in the activated sludge process that are responsible for an increase in percent MLVSS. These changes are the occurrence of a nutrient deficiency (see Chapter 7) and the occurrence of a slug discharge of soluble cBOD (see Chapter 15).

18

Colloidal Floc Particles

Colloidal floc particles contain relatively large quantities of colloids that hinder settleability. Because large numbers of water molecules often are bonded to the colloids that are adsorbed to floc particles, these particles may be known as hydrous floc particles.

COLLOIDS

Colloids share characteristics of molecules in solution and particles in suspension. Colloids are insoluble in wastewater and are complex in structure, with a relatively large surface area. Because of the large surface area, they do not settle out of wastewater. Colloids range in size from about 0.001 μm to about 0.1 μm. The small size of colloids results in the scattering of white light, which produces a turbid appearance in water.

In a healthy activated sludge process, colloids are adsorbed to the surface of floc particles. Their adsorption to floc particles is caused either by compatible charges between a floc particle and the colloid or by the coating action of ciliated protozoa and metazoa. Around pH 7, most colloids are negatively charged. Most negatively charged colloids are removed from the bulk solution of an activated sludge process by the coating action of ciliated protozoa and metazoa. Ciliated protozoa alone are responsible for removal of approximately 33% of the influent colloids to the activated sludge process.

Examples of colloids include proteins, petroleum droplets, and clay (Table 18.1). Many colloids, especially clays, have a layered structure. This structure permits the absorption of large numbers of water molecules between the layers. Because the colloids are hydrated, that is, possess water molecules, floc particles that have adsorbed significant quantities of colloids have indirectly adsorbed large quantities of water.

TABLE 18.1 Different Colloidal Molecules in Clay

Name of Colloidal Molecule	Formula
Hydrous media	$KAl_2(OH)_2(AlSi_3)O_{10}$
Kaolinite	$Al_2(OH)_4Si_2O_5$
Montmorillonite	$Al_2(OH)_2Si_4O_{10}$
Nontronite	$Fe_2(OH)_2Si_4O_{10}$

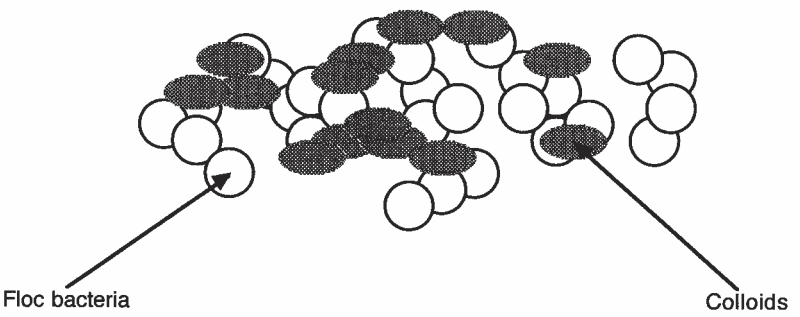

Figure 18.1 *Impact of colloids on settleability of a floc particle. Colloids do not settle out in the activated sludge process and are easily adsorbed to floc particles. Because most colloids degrade slowly in the activated sludge process, they contribute to an increase in the volatile content of the solids or floc particle. Colloids that cover the opening to the channels in the floc particle hinder the movement of water through the floc particle. For these reasons, colloids adversely affect solids settleability in the secondary clarifier.*

Unless sufficient HRT is provided in the aeration tank, most colloids are not degraded. Colloids that are not degraded contribute to increased volatile content of the mixed liquor and hinder the flow of water through the floc particle (Figure 18.1). Because colloids remain suspended in wastewater, increase the volatile content of the mixed liquor, and restrict the flow of water, they are responsible for settleability problems and loss of solids.

Although domestic wastewater contains colloidal waste in the form of proteins, domestic wastewater alone does not produce hydrous floc particles. Colloidal suspensions that are used in many industrial applications may be discharged to an activated sludge process and may contribute to the production of colloidal floc particles.

CONTROL

Several operational measures may be used to correct for the adverse impact of colloidal floc particles. These measures include the pretreatment of colloidal wastes and the addition of bioaugmentation products that contain bacteria with enzymatic ability to degrade colloids. Pretreatment of colloidal wastes may include ion absorption, ion replacement, and flocculation by polyelectrolytes.

19

Temperature

Temperature has a significant impact on the activity of all organisms in the activated sludge process and the development and settling character of floc particles (Figure 19.1). This impact causes physical and biological changes that affect floc particle structure and the settling rate of secondary solids.

PHYSICAL CHANGE

As wastewater temperature becomes colder, the wastewater becomes denser. Therefore, the settling rate of secondary solids decreases. However, the physical impact of cold temperature on the settling rate of secondary solids is not significant unless the MLVSS are relatively high, for example, >10,000 mg/l.

As wastewater temperature becomes warmer, the wastewater becomes less dense. Therefore, the settling rate of secondary solids increases during warm wastewater temperature. Again, the physical impact of warm temperature on secondary solids is not significant unless the MLVSS are relatively high.

BIOLOGICAL CHANGES

The impact of biological changes that affect floc particle structure and rate of settling of the secondary solids that are caused by changes in wastewater temperature occurs at relatively small MLVSS concentrations, for example, 2000 mg/l. The changes in the settling rate of secondary solids caused by changes in wastewater temperature are opposite to those changes caused by physical changes.

With increasing wastewater temperature, bacterial activity increases. Increased production and accumulation of insoluble biological secretions such as lipids and oils accompany this increase in activity. These secretions are adsorbed or entrapped

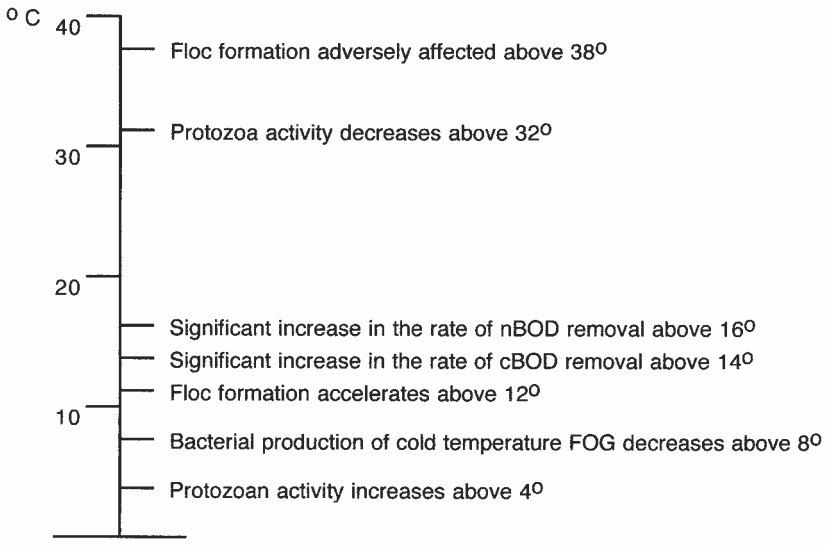

Figure 19.1 *Impact of temperature upon the activated sludge process. Changes in wastewater temperature have a significant impact upon the activity of all organisms, floc particle structure, and the rate of floc formation.*

by the floc particles, resulting in a decreased settling rate of secondary solids. When air bubbles or gases become entrapped in these secretions, the settling rate of the secondary solids decreases more.

With decreasing wastewater temperature, bacterial activity decreases. Decreased production and accumulation of insoluble biological secretions and a decreased number of entrapped air bubbles and gases accompany this decrease in activity. Therefore, the settling rate of the secondary solids is not as slow during decreasing wastewater temperature compared with increasing wastewater temperature.

CONTROL

Because increasing wastewater temperature and increased bacterial activity are critical factors that affect secondary solids settleability, a reduction in MLVSS concentration during warm wastewater temperature may be useful in preventing settleability problems and loss of solids. By reducing the MLVSS concentration, the amount of biological secretions that are produced and accumulated in floc particles is reduced.

If it is not possible to reduce the MLVSS concentration, alternate corrective measures are available to improve settleability. Bioagumentation products that have bacteria with the enzymatic ability to degrade the biological lipids and oils that are produced during warm wastewater temperature may be added to the aeration tank. The addition of a metal salt or polymer to the secondary clarifier influent to add weight to floc particles or improve floc density may be used.

Part III

Foam and Scum

20

Production and Accumulation of Foam and Scum

The production and accumulation of foam and scum in the activated sludge process is due to a change in at least one operational condition (Table 20.1). An activated sludge process may experience only one change in operational conditions or a combination of changes in operational conditions that produces foam. The presence of foam and scum in the activated sludge process results in many operational problems, including loss of treatment efficiency, increase in operational costs, and permit violations (Table 20.2).

Two characteristics are used to describe foam as it appears on the surface of an aeration tank. These characteristics are color and texture (Table 20.3). Sludge aging has an impact on the characteristics of the foam regardless of the change in operational condition responsible for foam production. Generally, with decreasing sludge age, foam becomes lighter in color and billowy in texture. With increasing sludge age, foam becomes darker in color and viscous in texture.

Although there are several operational conditions that produce foam, there is only one operational condition that produces scum. This condition is the death of large numbers of bacteria over a relatively short period of time. This usually is associated with toxicity.

FOAM

Foam is a film of solids, for example, lipids, that contain entrapped air bubbles or gases (Figure 20.1). The gases most often entrapped under a film of solids are carbon dioxide, molecular nitrogen, and nitrous oxide. When the entrapped air bubbles and gases escape from the foam, as happens when the foam spills over the influent weirs of the secondary clarifier, the foam collapses. The collapsed foam often is referred to as scum (Figure 20.2).

Several types of foam are produced in the activated sludge process (Table 20.3).

TABLE 20.1 Biological, Chemical, and Physical Conditions Responsible for the Production and Accumulation of Foam and Scum

Condition	Biological, Chemical, or Physical Change	Foam or Scum Production
Filamentous organisms	Biological	Foam
Nutrient deficiency	Biological	Foam
Sludge aging	Biological	Foam
Zoogloeal growth	Biological	Foam
Excess surfactants	Chemical	Foam
Increase in alkalinity	Chemical	Foam
Presence of cationic polymers	Chemical	Foam
Toxicity	Chemical	Scum
Accumulation of FOG	Physical	Foam

TABLE 20.2 Operational Problems Associated with the Production and Accumulation of Foam and Scum

Increased housekeeping
Increased operational costs
Loss of settleability
Loss of solids
Malodor production
Permit violations for BOD, TSS, and floating solids
Safety hazards

TABLE 20.3 Major Types of Foam Produced in the Activated Sludge Process

Foam	Texture and Color
Filamentous organism	Viscous chocolate brown
Nutrient deficiency	Billowy white (young sludge) Greasy gray (old sludge)
Sludge aging	Billowy white, crisp white, crisp brown, viscous dark brown, and gelatinous dark brown with debris
Zoogloeal growth	Billowy white
Excess surfactants	Billowy white
Increase in alkalinity	Billowy white
Presence of cationic polymers	Billowy white
Accumulation of FOG	Viscous dark brown or black

Depending on the type of foam produced and accumulated in the activated sludge process, the operational measures necessary to control foam production may vary. Therefore, it is important to properly identify the type of foam produced and the operational conditions responsible for its production. The identification of the foam produced should be made with an understanding that its production may be the result of several changes in operational conditions.

SCUM

Scum produced in the aeration tank is brown and flaky. Depending on the presence or absence of foam and the chemical composition of foam, there are four fates of

Figure 20.1 *Foam on the surface of an aerated lagoon.*

Figure 20.2 *Collapsed foam or scum on the surface of a secondary clarifier.*

scum in the aeration tank (Figure 20.3). If foam is absent in the aeration tank, the scum may leave the aeration tank and appear on the surface of the secondary clarifier. If the chemical composition of the foam is compatible with the scum, the scum may dissolve in the foam and darken the color of the foam. If the chemical composition of the foam is not compatible with the scum, the scum may appear as a brown flaky material on the surface of the foam. Finally, the scum may be degraded or adsorbed to floc particles in the aeration tank.

Scum is an insoluble and buoyant soap that floats to the surface of the aeration tank and secondary clarifier. Scum is produced when large numbers of bacteria die in the aeration tank. The death of large numbers of bacteria may occur because of seasonal changes in wastewater temperature or, more often, toxicity.

When bacteria die, they break open or lyse, and the cellular contents of the bacteria are released into the bulk solution. Fatty acids are a significant component of

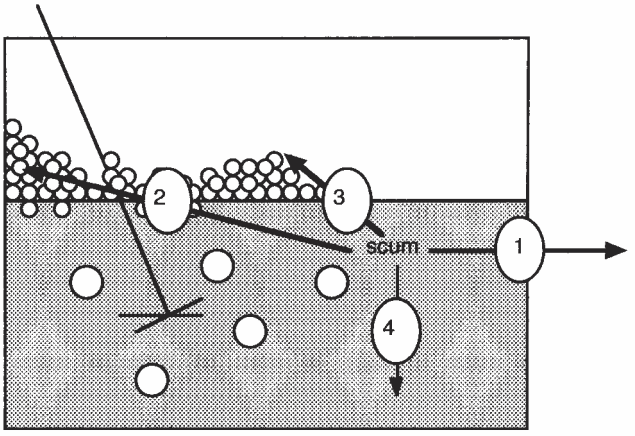

Figure 20.3 *Fate of scum in the activated sludge process. Scum produced in the aeration tank has one of four fates. First, scum may leave the aeration tank and appear on the surface of the secondary clarifier. Second, the scum may dissolve in the foam on the aeration tank. Third, scum may float on the surface of the foam on the aeration tank. Fourth, the viable bacteria in the aeration tank may degrade scum.*

the cellular contents that are released by the dead bacteria. In the bulk solution, the fatty acids may combine with the metal ions such as calcium (Ca^{2+}) and manganese (Mn^{2+}). If this occurs, an insoluble, buoyant, flaky brown soap or scum is produced. Because the term "scum" is often used to describe collapsed foam, scum on the surface of an aeration tank or secondary clarifier should be identified as either large numbers of dead bacteria or collapsed foam.

21

Identification of Foam

To correct operational problems associated with foam production and accumulation; it is necessary to properly identify the foam (Table 21.1). A troubleshooting flow schematic can be used to identify the foam that occurs in the activated sludge process (Figure 21.1). The use of the key is based on microscopic analyses of foam and mixed liquor, testing of wastewater samples, and review of appropriate operational data.

COLLECTING AND STORING WASTEWATER SAMPLES

Samples of foam, mixed liquor, and other wastewater samples that are needed for foam identification should be collected in clean, plastic screw-capped bottles. A small size , approximately 50 ml, is adequate for each sample. Care should be taken not to contaminate the mixed liquor with foam or foam with the mixed liquor. Wastewater samples that may need to be collected and used for identification of foam include digester feed sludge, centrate, filtrate, and primary clarifier effluent or mixed liquor influent.

Samples collected for the identification of foam may be used immediately after collection or stored for up to 1 week. Samples that are stored should be placed in clean, plastic screw-capped bottles and refrigerated at 4°C (±1°C). All sample bottles should be labeled with date, time, and location of the sample as well as the color and texture of the sample. At least one-half of the volume of the sample bottle should contain an air space. Refrigerated samples should be allowed to come to room temperature and should be stirred before they are used.

FILAMENTOUS ORGANISMS

Foam produced by filamentous organisms is viscous and chocolate brown. This foam typically has foam-producing filamentous organisms in higher density than in the

TABLE 21.1 Major Types of Foam Produced in the Activated Sludge Process

Foam	Texture and color
Filamentous organism	Viscous chocolate-brown
Nutrient deficiency	Billowy white (young sludge) Greasy gray (old sludge)
Sludge aging	Billowy white, crisp white, crisp brown, viscous dark brown, and gelatinous dark brown with debris
Zoogloeal growth	Billowy white
Excess surfactants	Billowy white
Increase in alkalinity	Billowy white
Presence of cationic polymers	Billowy white
Accumulation of FOG	Viscous dark brown or black

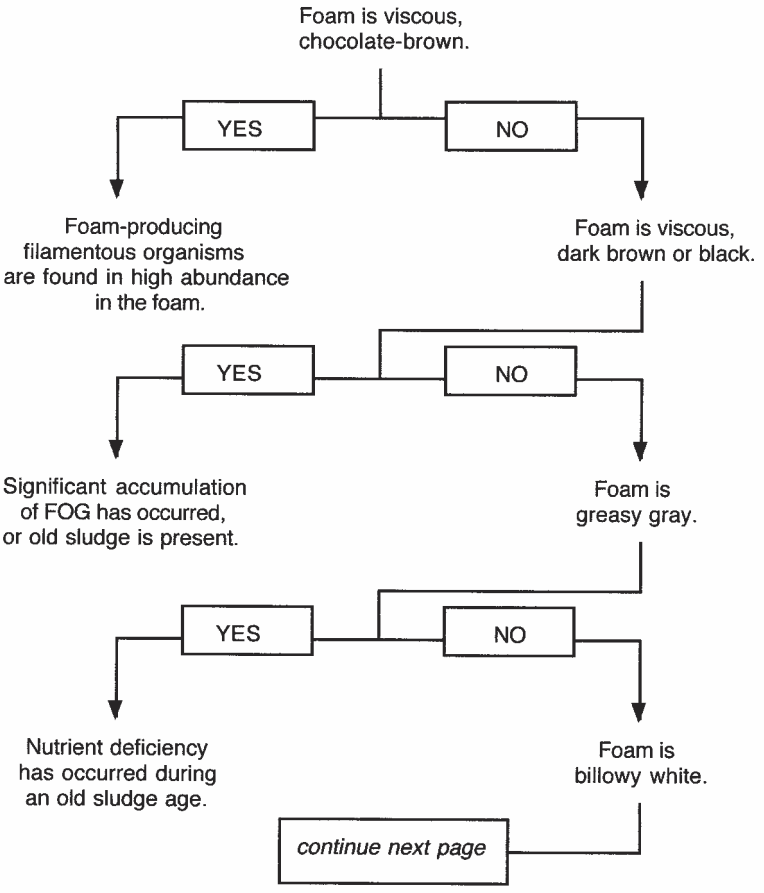

Figure 21.1 *Identification of the operational condition responsible for foam production.*

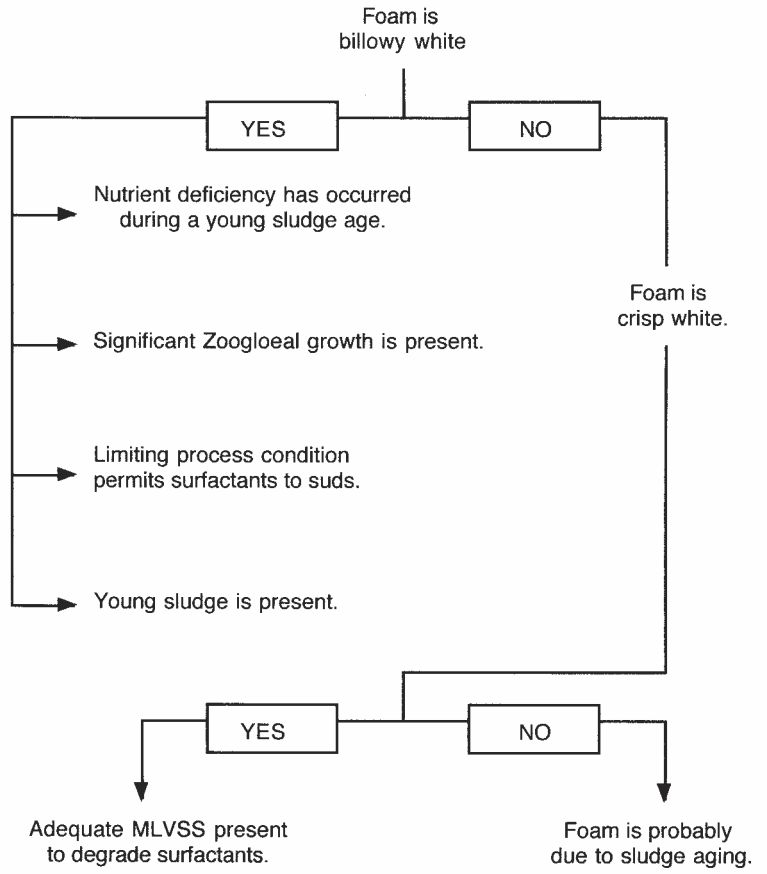

Figure 21.1 *Continued*

mixed liquor. To determine whether foam-producing filamentous organisms are responsible for foam production in the activated sludge process, the following procedure is recommended:

1) A wet mount of mixed liquor should be examined, and a subjective evaluation of the amount of filamentous organisms in the mixed liquor should be made.
2) A smear of foam should be examined, and a subjective evaluation of the amount of filamentous organisms in the smear should be made.
3) If the filamentous organisms in the foam are present at a lower density than in the mixed liquor, it is not likely that foam-producing filamentous organisms are responsible for foam production.
4) If the filamentous organisms in the foam are present at a higher density than in the mixed liquor, it is possible that the foam-producing filamentous organisms are responsible for foam production. Gram staining and Neisser staining of smears of foam should be performed to determine the relative density of the filamentous organisms, especially the translucent type 0092.

TABLE 21.2 Foam-Producing Filamentous Organisms

Filamentous Organism	Know Foam Producer	Suspect Foam Producer
Microthrix parvicella	X	
Nocardioforms	X	
Nostocoida limicola		X
Type 0041		X
Type 0092		X
Type 0581		X
Type 0961		X
Type 1863	X	

5) Because many filamentous organisms do not produce foam, for example, *Sphaerotilus natans*, type 021N, and type 1701, but may be found in foam, it is necessary to identify the dominant filamentous organisms in the foam to see whether they are foam-producing filamentous organisms (Table 21.2).

If the dominant filamentous organisms in viscous, chocolate brown foam are foam-producing filamentous organisms and are present at a higher density than in the mixed liquor, these filamentous organisms are contributing to foam production.

NUTRIENT DEFICIENCY

Foam produced by nutrient-deficient floc particles is billowy white at a young sludge age and greasy gray at an old sludge age. To determine whether foam production is due to nutrient-deficient floc particles in the activated sludge process, the following procedure is recommended:

1) Collect and filter a sample of mixed liquor effluent during peak loading conditions when soluble cBOD from an industrial discharge is present. Analyze the filtrate from the mixed liquor for quantities of ammonium ions and orthophosphate ions to determine whether target values for readily available nutrients are present.
2) Perform an India ink reverse stain on a wet mount of mixed liquor effluent collected during peak loading conditions. Determine whether most floc particles test negatively or positively to the India ink reverse stain.
3) Identify any dominant filamentous organisms in the mixed liquor and list their appropriate operational growth conditions.

An indicator of a nutrient deficiency in the activated sludge process is the presence of concentrations of ammonium ions and orthophosphate ions in the mixed liquor effluent filtrate that are less than the recommended target values of 1.0 mg/l for NH_4^+ and 0.5 mg/l for HPO_4^{2-}. Additional indicators of a nutrient deficiency include positive India ink reverse stains for most floc particles in a wet mount of mixed liquor and the presence of filamentous organisms that grow rapidly during a nutrient deficiency (Table 21.3). If these indicators occur when billowy white foam

TABLE 21.3 Filamentous Organisms That Proliferate Rapidly during a Nutrient Deficiency

Type 021N
Type 0041
Type 0675
Type 1701
Fungi
Haliscomenobacter hydrossis
Nocardioforms
Sphaerotilus natans
Thiothrix spp.

(young sludge age) or greasy gray foam (old sludge age) is present, a nutrient deficiency should be suspected as contributing to foam production.

SLUDGE AGING

Several types of biological foam are produced through sludge aging. These types include billowy white, crisp white, crisp brown, viscous dark brown, and gelatinous dark brown with debris. If foam other than foam produced through sludge aging cannot be demonstrated, than foam produced through sludge aging should be suspected. The types of foam produced through sludge aging can be correlated with sludge age, floc particle structure, secondary clarifier effluent solids, and dominant protozoa and metazoa in the activated sludge (Figure 21.2).

Billowy White Foam

Billowy white foam is produced when a relatively small population of bacteria or low MLVSS concentration, for example, <1000 mg/l, is present. When a small population of bacteria is present in the activated sludge, surfactants are not adequately degraded. The nondegraded surfactants produce suds or billowy white foam.

Crisp White Foam

Crisp white foam is produced when the activated sludge process is operating properly. An adequate population of bacteria is present to degrade the surfactants in the waste stream. Because of the degradation of surfactants and the presence of only a relatively small amount of biological secretions in the floc particles, the foam on the aeration tank is crisp white.

Crisp Brown Foam

Crisp brown foam is produced during an old sludge age when large quantities of biological secretions (lipids and oils) have been adsorbed by the floc particles. The absorbed secretions entrap air bubbles and gases, and the brown color of the collected secretions darkens the foam. Crisp brown foam is expected in an extended

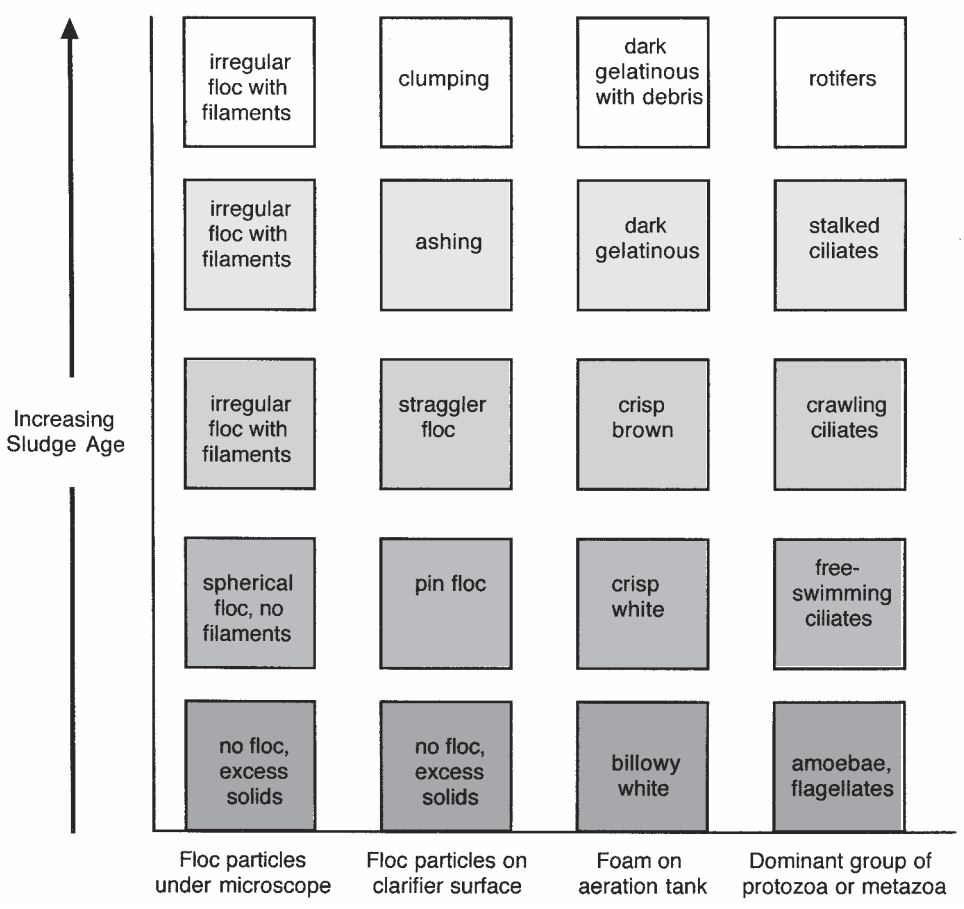

Figure 21.2 *Aging floc particles, foam, protozoa, filamentous organisms, and metazoa. With increasing sludge age, several significant changes occur in the development of the floc particle, foam, dominant protozoa groups, the presence of filamentous organisms, and the appearance of metazoa. Changes in the development of the floc particle can be observed through microscopic examination or can be observed in the type of floc particles that appear on the surface of the secondary clarifier. Changes in foam can be observed with respect to its texture and color, and the dominant protozoan group and appearance of large numbers of metazoa can be correlated with increasing treatment efficiency.*

aeration process that is operating properly. Crisp brown foam occurs in a conventional activated sludge process that is operating with an old sludge.

Viscous Dark Brown Foam

Viscous dark brown foam is produced in an activated sludge process with an extremely old sludge. Because of the old sludge age, large numbers of slow-growing, foam-producing filamentous organisms may be present. Large quantities of lipids from foam-producing filamentous organisms, secretions from old floc bacteria, and the presence of entrapped air bubbles and gases are responsible for the production of viscous dark brown foam.

Gelatinous Dark Brown Foam With Debris

Gelatinous dark brown foam with debris is produced in an activated sludge process when significant quantities of particulate material have been adsorbed to floc particles. Significant quantities of particulate material are removed from the bulk solution in a very stable activated sludge process. This process has numerous bacteria and relatively large and active populations of ciliated protozoa and metazoa.

ZOOGLOEAL GROWTH

Foam produced by Zoogloeal growth is billowy white. To determine whether foam production is due to Zoogloeal growth in the activated sludge process, the following procedure is recommended:

1) A wet mount of mixed liquor should be examined for the presence of amorphous or dendritic Zoogloeal growth.
2) If Zoogloeal growth is found, its relative abundance (significant or insignificant) should be determined.

If significant Zoogloeal growth is found and billowy white foam is present on the surface of the aeration tank, Zoogloeal growth should be suspected as contributing to foam production.

EXCESS SURFACTANTS

The presence of excess surfactants or limiting process conditions that mimic excess surfactants results in the production of suds or billowy white foam (Table 21.4). To determine whether foam production is due to surfactants, chemical analyses of the surfactant concentration in the mixed liquor influent should be performed according to the latest edition of *Standard Methods*. If a significant increase in surfactant concentration occurs without an increase in MLVSS concentration or the presence of a limiting process condition occurs, the presence of excess surfactants should be suspected as contributing to foam production.

INCREASE IN ALKALINITY

An increase in alkalinity in the activated sludge process results in a change in the surface tension of the mixed liquor. This change in the surface tension permits the

TABLE 21.4 Limiting Process Conditions That Permit Foam Production from Surfactants

Low MLVSS concentration (<1000 mg/l)
Slug discharge of surfactants
Toxicity

production of billowy white foam. An increase in alkalinity may occur through the discharge of alkali wastes, for example, ammonium ions, to the activated sludge process or through the discharge of organic-nitrogen compounds such as proteins that release ammonium ions when they degrade.

To determine whether foam production is due to an increase in alkalinity, chemical analyses of mixed liquor influent samples for the quantity of alkalinity and total Kjeldahl nitrogen (TKN) should be performed according to the latest edition of *Standard Methods*. TKN measures the amount of organic-nitrogen compounds in a wastewater sample. Mixed liquor influent TKN provides an estimate of the amount of ammonium ions that can be released when organic-nitrogen compounds degrade. Approximately 2 mg/l ammonium ions are released for every 5 mg/l of organic-nitrogen compounds degraded.

If significant increases in the concentrations of mixed liquor influent alkalinity and TKN occur, an increase in alkalinity should be suspected as contributing to foam production.

PRESENCE OF CATIONIC POLYMERS

Cationic polymers, especially polyacrylamide polymers, are commonly used at activated sludge processes to capture solids, dewater solids (sludges), and thicken solids (sludges). Cationic polyacrylamide polymers contain two compounds, acrylamide and acrylic acid (Figure 21.3). The acrylic acid is bonded to a quaternary amine. If cationic polyacrylamide polymers are misapplied or used in excess and the polymer enters the activated sludge process, billowy white foam may be produced.

Production of billowy white foam is the result of the degradation of the polymer. When the polymer degrades, amino groups ($-NH_2$) are released in the aeration tank. These groups are converted quickly to ammonium ions (NH_4^+). The ammonium ions cause an increase in alkalinity that changes the surface tension of the mixed liquor, resulting in the production of billowy white foam.

To determine whether foam production is due to the presence of cationic polyacrylamide polymers, the following procedure is recommended:

1) Collect a sample of the suspect waste stream that has been exposed to the polymer, for example, primary clarifier effluent, centrate, or filtrate.
2) Collect a sample of digester feed sludge that is being transferred to the sludge dewatering unit. Be sure that the feed sludge has not been exposed to the polymer that is used for sludge dewatering.

Figure 21.3 *Chemical compounds in cationic, polyacrylamide polymers. Cationic polyacrylamide polymers contain acrylamide and acrylic acid. The acrylic acid contains a quaternary amine. When cationic polyacrylamide polymers degrade in an aeration tank; the amino group ($-NH_2$) and the quaternary amine are released. These released compounds are quickly converted to ammonium ions (NH_4^+) in the aeration tank. The ammonium ions produce an increase in alkalinity and change the surface tension of the wastewater that permits foaming to occur.*

3) Gently and slowly mix together approximately 50 ml of the suspect waste stream and approximately 50 ml of the digester feed sludge in a clean beaker and allow the mixed samples to sit undisturbed. If the digester feed sludge flocculates, then the suspect waste stream contains excess polymer.

If excess cationic polyacrylamide polymer is present in a waste stream that enters the activated sludge process and billowy white foam is present on the surface of the aeration tank, excess cationic polyacrylamide polymer should be suspected as contributing to foam production.

ACCUMULATION OF FOG

The accumulation of FOG on the surface of floc particles produces viscous dark brown or black foam. Petroleum oils and grease are responsible for viscous black foam. To determine whether foam production is due to the accumulation of FOG, the following procedure is recommended:

1) A wet mount of mixed liquor should be examined for the presence of a coating of FOG on numerous floc particles, and an India ink reverse stain of a wet mount should be examined to determine the presence of oil droplets that contain dispersed growth and small floc particles.
2) Oil and grease analyses of mixed liquor influent should be performed according to the latest edition of *Standard Methods* to determine whether elevated concentrations of oils and grease are present.
3) Analyses of the percent MLVSS should be made to determine whether a significant increase in percent MLVSS has occurred.

If the microscopic analyses reveal the presence of FOG and there are significant increases in mixed liquor influent FOG concentration and percent MLVSS, the accumulation of FOG should be suspected as contributing to foam production.

22

Controlling Foam Production and Accumulation

There are many control measures for preventing foam production and reducing the quantity of foam accumulated on the surface of an aeration tank (Tables 22.1–22.8). Some measures, for example, the use of impact sprayers or bib sprayers to collapse or dilute foam, may be used for many types of foam, whereas others such as the use of surfactant degrading bacteria can be used for only one foam—surfactant foam.

FOAM PRODUCED BY FILAMENTOUS ORGANISMS

The undesired growth of foam-producing filamentous organisms is usually associated with viscous chocolate brown foam. The foam typically has filamentous organisms present in much higher density than the mixed liquor.

To control foam production and accumulation in the aeration tank from foam-producing filamentous organisms, several operational measures are available. The growth of foam-producing filamentous organisms should be controlled, and the operational conditions responsible for the undesired growth of foam-producing filamentous organisms should be identified and corrected.

Spraying the foam with effluent water through a bib sprayer or lawn sprinkler can reduce the quantity of foam on the surface of an aeration tank. When applied through a bib sprayer, the effluent water dilutes the foam and permits the foam to collapse.

Foam may be vacuumed or raked from the surface of the aeration tank. Because the foam contains a relatively large number of viable filamentous organisms, appropriate treatment and disposal of the foam should be exercised so as not to place viable foam-producing filamentous organisms back into the activated sludge process.

Because the foam is made from biological lipids, dusting and collapsing the foam with an appropriate polymer may be performed. The collapsed foam may be

TABLE 22.1 Operational Measures for Controlling Foam Produced by Filamentous Organism (See Chapter 6)

X if applicable	Operational Measure
	Correct undesired growth of filamentous organisms
	Dilute and collapse foam with bib sprayers
	Vacuum/rake foam from the aeration
	Dust and collapse foam with polymer and vacuum/rake foam from the aeration tank
	Treat mixed liquor and foam with lipase producing bioaugmentation products
	Treat foam with sodium hypochlorite solution
	Treat foam with defoaming agent

TABLE 22.2 Operational Measures for Controlling Foam Produced by a Nutrient Deficiency (See Chapter 7)

X if applicable	Operational Measure
	Correct nutrient deficiency
	Dilute and collapse foam with bib sprayers
	Vacuum/rake foam from the aeration

Table 22.3 Operational Measures for Controlling Foam Produced by Sludge Aging (See Chapter 14)

X if applicable	Operational Measure
	Billowy white—increase the sludge age
	Crisp white—no change in sludge age is equired
	Crisp brown—decrease the sludge age
	Viscous dark brown—decrease the sludge age
	Gelatinous dark brown with debris

Table 22.4 Operational Measures for Controlling Foam Produced by Zoogloeal Growth (See Chapter 16)

X if applicable	Operational Measure
	Correct operational conditions associated with Zoogloeal growth
	Dilute and collapse foam with bib sprayers
	Use anoxic periods or zones
	Treat Zoogloeal growth with appropriate polymer

Table 22.5 Operational Measures for Controlling Foam Produced by Surfactants (See Chapter 10)

X if applicable	Operational Measure
	Source control or pretreatment of surfactants
	Dilute or collapse foam with bib sprayers
	Increase MLVSS
	Treat mixed liquor with surfactant degrading bioaugmentation products
	Correct operational conditions that mimic a young sludge age

Table 22.6 Operational Measures for Controlling Foam Produced by Increase in Alkalinity

X if applicable	Operational Measure
	Source control or pretreatment of alkalinity
	Dilute or collapse foam with bib sprayers
	Reduce the quantity of alkalinity in the aeration tank

Table 22.7 Operational Measures for Controlling Foam Produced by Cationic Polymers

X if applicable	Operational Measure
	Proper selection of cationic polymers
	Proper application of cationic polymers

Table 22.8 Operational Measures for Controlling Foam Produced by the Accumulation of FOG (See Chapter 17)

X if applicable	Operational Measure
	Source control or pretreatment of FOG
	Collapse foam with impact sprayers
	Increase WAS rate
	Treat mixed liquor and foam with bioaugmentation products having the enzymatic ability to degrade FOG

vacuumed or raked from the surface of the aeration tank. The lipid-based foam as well as mixed liquor that contains lipid-coated floc particles may be treated with bioaugmentation products containing lipase enzymes. These enzymes, when produced and released by the bacterial products, degrade lipids.

The foam and the filamentous organism within the foam may be sprayed with a 10–15% sodium hypochlorite solution. The hypochlorite solution should remain in contact with the foam for 2–3 hours, and the foam should be collapsed with a spray of effluent water. The hypochlorite solution oxidizes the chemical bonds in the lipids and attacks the filamentous organisms in the foam. The foam is more easily collapsed when the lipids are oxidized and the number of viable filamentous organisms in the foam is greatly reduced through chlorine destruction.

The foam also may be treated with a defoaming agent. A defoaming agent commonly used for foam produced by foam-producing filamentous organisms is a polyglycol-based defoaming agent. The use of a petroleum-based defoaming agent can collapse the foam, but the agent may serve as a substrate for the continued growth of foam-producing filamentous organisms.

FOAM PRODUCED BY NUTRIENT DEFICIENCY

A nutrient deficiency in the activated sludge process usually is associated with the production of billowy white foam (young sludge age) or greasy gray foam (old

sludge age). The secretions of insoluble polysaccharides inside floc particles during a nutrient deficiency are responsible for the production and accumulation of billowy white foam or greasy gray foam.

To control foam production and accumulation in the aeration tank from a nutrient deficiency, several operational measures are available. The degradation of stored polysaccharides within floc particles should be corrected with the addition of the appropriate nutrients, and the operational conditions responsible for the nutrient deficiency should be identified and corrected.

Spraying the foam with effluent water through a bib sprayer or lawn sprinkler can reduce the quantity of foam on the surface of an aeration tank. When applied through a bib sprayer, the effluent water dilutes and collapses the foam.

Foam may be vacuumed or raked from the surface of the aeration tank. Because the foam may contain a relatively large number of viable filamentous organisms, appropriate treatment and disposal of the foam should be exercised so as not to place these filamentous organisms back into the activated sludge process.

FOAM PRODUCED BY SLUDGE AGING

Several types of foam are produced during sludge aging. These types of foams are billowy white, crisp white, crisp brown, viscous dark brown, and gelatinous dark brown with debris. Billowy white foam may be corrected by increasing the sludge age of the activated sludge process. This is achieved by decreasing the WAS rate. Crisp brown foam is typical of a properly operating activated sludge process and requires no change in the sludge age. Viscous dark brown foam and gelatinous dark brown foam with debris are typical of an old sludge age. These foams may be corrected by decreasing the sludge age of the activated sludge process. This is achieved by increasing the WAS rate.

FOAM PRODUCED BY ZOOGLOEAL GROWTH

Billowy white foam may be produced during Zoogloeal growth. This foam is the result of the entrapment of air bubbles and gases by the copious quantity of gelatinous materials secreted by rapidly growing floc-forming bacteria.

Operational conditions associated with the Zoogloeal growth should be identified and corrected. Foam from Zoogloeal growth and Zoogloeal growth itself may be controlled through several operational measures.

Spraying the foam with effluent water through a bib sprayer or lawn sprinkler can reduce the quantity of foam on the surface of an aeration tank. When applied through a bib sprayer, the effluent water dilutes and collapses the foam.

Because many floc-forming bacteria are strict aerobes, the use of anoxic periods or anoxic zones can slow their rapid growth. An anoxic period or zone of at least 1–2 hours may be successful in controlling Zoogloeal growth and its associated billowy white foam.

An anoxic period is produced in an aeration tank when nitrate ions (NO_3^-) are present and the dissolved oxygen feed (aeration) is terminated. The use of nitrate ions by bacteria for the degradation of soluble cBOD for 1–2 hours is considered

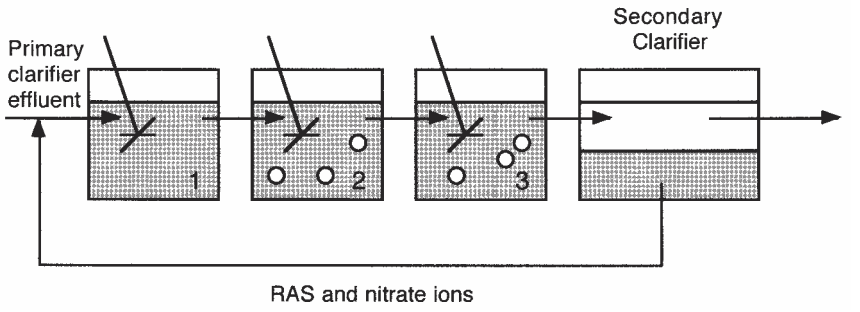

Figure 22.1 *Use of an anoxic tank in plug-flow mode of operation to control Zoogloeal growth. Zoogloeal growth may be controlled by using an anoxic tank in plug-flow mode of operation. In this mode of operation, solids and nitrate ions are removed from the floor of the secondary clarifier at an increased RAS rate. The solids and nitrate ions are returned to the first aeration tank. The tank is mixed and either not aerated or aerated only slightly to ensure mixing. The primary clarifier effluent that contains soluble cBOD is fed to the first aeration tank. The solids (bacteria) in the first tank along with nitrate ions and soluble cBOD are responsible for the production of an anoxic condition. Zoogloeal growth cannot survive in an anoxic tank and does not use nitrate ions efficiently to degrade soluble cBOD.*

an adequate anoxic period. Nitrate ion concentration should always be present in the aeration tank during the anoxic period.

An anoxic zone can be established in an activated sludge process by using the plug-flow mode of operation (Figure 22.1). In the plug-flow mode of operation the nitrate ions produced in the activated sludge process are returned from the secondary clarifier to the first aeration tank. The first aeration tank is not aerated. In the first aeration tank, influent soluble cBOD is degraded through bacterial activity with nitrate ions. Because strict aerobe floc-forming bacteria cannot degrade soluble cBOD by using nitrate ions, their growth is slowed.

The gelatinous materials secreted by rapidly growing floc-forming bacteria may be treated with a polymer. The polymer selected for use may be cationic or anionic depending on the net charge of the gelatinous materials.

FOAM PRODUCED BY SURFACTANTS

Excess surfactants in the activated sludge process may cause sudsing or the production and accumulation of billowy white foam on the surface of the aeration tank. The best measure for the control of surfactant foam is the regulation and pretreatment of surfactants. Significant dischargers of surfactants should be identified, and surfactants should be removed from the waste stream or pretreated. Pretreatment may include the use of bioaugmentation products that degrade surfactants. If large quantities of surfactants are discharged to the sewer system, the discharge should be equalized over as long a period of time as possible.

Surfactant foam may be collapsed with the use of bib sprayers or may be degraded with an increase in MLVSS concentration. If MLVSS concentration cannot be increased, the addition of bioaugmentation products with the enzymatic ability to degrade surfactants may be used.

Operational conditions that mimic a young sludge age or relatively small concentration of MLVSS should be identified and corrected. These conditions include toxicity and excessive wasting of MLVSS.

FOAM PRODUCED BY AN INCREASE IN ALKALINITY

Excess alkalinity in the aeration tank results in a change in the surface tension of the mixed liquor. This change causes sudsing or the production of white billowy foam. The best measure for the control of alkalinity foam is the regulation and pretreatment of alkalinity or alkalinity-producing wastes. These wastes include ammonium ions and nitrogenous wastes that release ammonium ions when they degrade in the aeration tank. Examples of nitrogenous wastes that release ammonium include proteins, cationic polymers, and surfactants.

Alkalinity foam may be collapsed with the use of bib sprayers or by changing the HRT in the aeration tank. Decreasing the HRT prevents the degradation of nitrogenous wastes and the release of ammonium ions. Increasing the HRT encourages nitrification and the oxidation of ammonium ions to nitrate ions. Depending on discharge permit requirements, for example, ammonia and total nitrogen limitations, an activated sludge process may not be able to change the HRT of its aeration tanks.

Removing an aeration tank from service decreases the HRT of an aeration tank that is in-line. Lowering the RAS rate or placing an additional aeration tank in service increases the HRT of an aeration tank that is on-line.

FOAM PRODUCED BY CATIONIC POLYMERS

Cationic polymers are used to capture solids, thicken solids, and dewater solids. The solids that are treated with cationic polymers contain mostly bacteria. Because the characteristics of bacteria change with changing operational conditions, the percent charge and amount of polymer needed for capturing, thickening, and dewatering solids also changes. Therefore, periodic testing to determine the proper charge and dose of the polymer and the injection point of the polymer used should be performed to prevent loss of excess polymer to the activated sludge process.

FOAM PRODUCED BY FOG

The accumulation of FOG on floc particles in the activated sludge process results in the entrapment of air bubbles and gases and the production and accumulation of viscous dark brown or black foam. There are several operational measures that may be used to control the accumulation of FOG and the production and accumulation of foam.

Wherever possible, significant dischargers of FOG should be identified and FOG should be pretreated or removed from the waste stream. If discharges of FOG are

permitted, these discharges should be equalized over as long a period of time as possible.

The accumulation of foam on the surface of the aeration tank may be broken or collapsed with the use of impact sprayers, and the quantity of FOG within the aeration tank may be reduced by increasing the WAS rate. FOG is easily and quickly adsorbed to floc particles. Therefore, increasing the WAS rate to remove more solids or floc particles also removes FOG.

Pretreatment with bioaugmentation products with the enzymatic ability to degrade FOG should be considered as well as the addition of the same bioaugmentation products to the activated sludge system. As the enzymes degrade the FOG, less entrapment of air bubbles and gases occurs and a decrease in foam production and accumulation results.

Part IV

Settleability Testing

23

Settleability Testing and Settling Rate

The settling character of activated sludge or secondary solids is commonly evaluated by its SVI, or sludge volume index (Appendix I). The SVI measures the volume per gram (ml/g) or compaction of secondary solids. An SVI between 80 and 120 ml/g usually indicates good settling secondary solids. An SVI greater than 150 ml/g indicates the presence of poorly settling solids.

Several settleability tests are used to determine the settling character of secondary solids. These tests include the standard SVI, the diluted SVI, and the stirred specific volume index (SSVI). Although these tests reveal how well or how poorly secondary solids settle over a period of time, usually 30 minutes, they do not reveal the operational conditions that produce secondary solids that settle well or poorly. Microscopic, biological, and chemical analyses do reveal the operational conditions that produce secondary solids that settle well or poorly. These analyses reveal operational conditions, for example, undesired filamentous growth, nutrient deficiency, and denitrification, that are responsible for the settling character of the secondary solids.

A component of the settleability test that is often overlooked is the setting rate of the secondary solids. The settling rate is determined by calculating the volume of settled solids (ml) per minute from time "zero" to ten minutes during a 30-minute settleability test. The settling rate may be used to determine whether secondary solids may be lost from the clarifier, regardless of the SVI.

Just as each activated sludge process has a range of SVIs that are best for its secondary solids, each activated sludge process has a range of settling rates that are best for its secondary solids. Although secondary solids may have settled to an acceptable SVI after 30 minutes, the settling rate of the settleability test, if too rapid or too slow, may indicate the potential loss of secondary solids from the clarifier. If the settling rate is too slow, the loss of secondary solids may occur during an increase in hydraulic flow, for example, I/I or bypassing of a treatment tank upstream of the

secondary clarifier. If the settling rate is too rapid, fine solids that are not filtered out by the settling solids, may be lost from the secondary clarifier.

Many activated sludge processes are operated to achieve an SVI within an acceptable range. These same activated sludge processes also should attempt to achieve a settling rate within an acceptable range.

24

Settleability Testing: Microscopic Analyses

Although the SVI and the settling rate obtained through a settleability test are important measurements of the settling character of secondary solids, they do not reveal why the secondary solids settle well or poorly. Also, these measurements do not reveal the operational conditions that are responsible for the production of floating solids, foam, and poor-quality supernatant. Microscopic analyses of floating solids, foam, supernatant, and settled solids developed during a settleability test do reveal the operational conditions responsible for the settleability results in the settleability test and the settleability problems and loss of solids in the secondary clarifier.

When SVIs and settling rates are acceptable, periodic microscopic analyses of the settled solids and supernatant in the graduate cylinder or settleometer used for the settleability test should be performed. The results of the analyses may be recorded in a log or through the use of photomicrography. When the SVIs and settling rates are unacceptable, microscopic analyses of the settled solids as well as floating solids, foam, and supernatant should be performed.

Recommended microscopic analyses include the quality of the bulk solution, floc particle profile, filamentous organism profile, and protozoa profile (Table 24.1). Microscopic analyses of solids produced during acceptable and unacceptable SVIs should be compared to reveal the biological and operational conditions responsible for settleability problems and loss of solids.

Besides microscopic analyses of activated sludge samples from in-line aeration tanks, several other wastewater samples may be used to identify operational conditions responsible for settleability problems and loss of solids (Table 24.2). Examples can be offered to illustrate the usefulness of additional samples to identify undesired operational conditions. Samples of RAS before and after RAS pumps can be used to determine whether the RAS pump is responsible for shearing action. Samples of RAS before and after RAS pumps at different RAS rates can be used to determine at what RAS rates unacceptable shearing action occurs. Recycle

TABLE 24.1 Components of Microscopic Analyses of Contents of a Settleability Test

Component	Analyses
Bulk solution	Relative abundance of dispersed growth
	Relative abundance of particulate material
Filamentous organisms	Dominant and recessive filamentous organisms
	Presence of foam-producing filamentous organisms
	Relative abundance of filamentous organisms
	Significant interfloc bridging
	Significant open floc formation
Foam	Presence of foam-producing filamentous organisms
	Presence of nutrient-deficient floc particles
	Presence of Zoogloeal growth
Floc particles	Nutrient deficiency
	Relative abundance of filamentous organisms
	Strength and density
	Viscous floc or Zoogloeal growth
Protozoa	Acceptable activity
	Acceptable structure
	Dominant and recessive protozoan groups
	Relative abundance of the community

TABLE 24.2 Wastewater Samples that May Be Useful for Detecting Unacceptable Operational Conditions

Leachate
Mixed liquor effluent from an in-line tank
Mixed liquor effluent from in-line tanks of parallel system
Effluent from pretreated industrial discharge
Recycle streams (aerobic digester, anaerobic digester, DAF effluent, primary clarifier effluent, RAS before and after RAS pump, sludge dewatering units, thickener overflow)
Secondary clarifier effluent solids
Secondary clarifier foam and scum
Solids from clarifier sludge blanket

streams can be examined to determine the presence of undesired filamentous growth that may seed the activated sludge process. Clarifier scum and aeration tank foam samples may be compared to determine whether the clarifier scum is simply collapsed foam.

Appendix I

F/M, HRT, MCRT, MLVSS, Sludge Age, SVI

F/M

The food-to-microorganism ratio or F/M is a measurement of the food entering the activated sludge process and the microorganisms (bacteria) in the aeration tanks. Each activated sludge process has a range of F/M values at which it operates best. The F/M may fluctuate throughout the year according to changes in operational conditions including industrial discharge, permit requirements, or seasonal wastewater temperature. The range of F/M may change on a seasonal basis, for example, higher F/M during the summer and lower F/M during the winter.

The amount of food (**F**) entering the activated sludge process consists of the quantity (loading or pounds) of BOD discharged to the aeration tanks. The BOD loading is calculated by multiplying the concentration (mg/l) of BOD entering the aeration tanks by the influent flow per day (millions of gallons per day, or MGD) to the aeration tanks by the weight constant of 8.34 pounds per gallon of wastewater (Equation I.1).

$$\text{BOD (mg/l)} \times \text{flow (MGD)} \times 8.34\,\text{pounds/gallon of wastewater} = \text{BOD loading} \quad \text{(I.1)}$$

The amount of microorganisms (**M**) in the activated sludge process consists of the pounds of mixed liquor volatile suspended solids (MLVSS) in the on-line aeration tanks. The pounds of MLVSS are calculated by multiplying the concentration (mg/l) of MLVSS by the volume of the aeration tanks in million gallons (MG) by the weight constant of 8.34 pounds per gallon of wastewater (Equation I.2).

$$\text{MLVSS (mg/l)} \times \text{aeration tank volume (MG)} \times 8.34\,\text{pounds/gallon of wastewater} = \text{pounds MLVSS} \quad \text{(I.2)}$$

The F/M of an activated sludge process can be calculated by dividing the pounds of food as BOD to the aeration tanks by the pounds of microorganisms (bacteria) present in the on-line aeration tanks (Equation I.3). The F/M is simply Equation I.1 divided by Equation I.2.

$$\text{F/M} = \text{pounds BOD to the aeration tank/pounds of MLVSS in the on-line aeration tanks} \quad \text{(I.3)}$$

HRT

The hydraulic retention or HRT of an aeration tank is the amount of time in hours for wastewater to pass through the aeration tank. Changes in HRT can affect biological activity. For example, decreasing HRT adversely affects nitrification and the solubilization of particulate BOD and colloidal BOD. Decreasing HRT also permits the discharge of more BOD to the receiving stream. Increasing HRT favors nitrification and the solubilization of particulate BOD and colloidal BOD. Increasing HRT also permits the discharge of less BOD to the receiving stream.

The HRT of an aeration tank is determined by dividing the volume of the aeration tank (gallons) by the flow rate through the aeration tank (Equation I.4). The flow rate through the aeration tank must be expressed as gallons per hour (gph).

$$\text{HRT (hours)} = \text{(volume of aeration tank, gallons)/(flow rate, gph)} \quad \text{(I.4)}$$

MCRT

The mean cell residence time or MCRT is the amount of time, in days, that solids or bacteria are maintained in the activated sludge process. The MCRT is known also as the solids retention time (SRT). To calculate the MCRT, it is necessary to know the amount of suspended solids (pounds) in the activated sludge process and the amount of suspended solids (pounds) leaving the activated sludge process.

To determine the pounds of suspended solids in the activated sludge process, the pounds of mixed liquor suspended solids (MLSS) must be calculated. The MLSS consists of all solids in the aeration tanks and secondary clarifiers. Therefore, the pounds of MLSS in the activated sludge process consists of the concentration (mg/l) of MLSS times the volume (MG) of the aeration tanks and secondary clarifiers times the weight constant of 8.34 pounds per gallon of wastewater (Equation I.5).

$$\text{Pounds of MLSS} = \text{MLSS (mg/l)} \times \text{(volume of aeration tanks, MG + volume of secondary clarifiers, MG)} \times 8.34 \text{ pounds/gallon of wastewater} \quad \text{(I.5)}$$

To determine the pounds of suspended solids leaving the activated sludge process, the pounds of suspended solids lost through wasting and discharged in the secondary effluent must be calculated. Therefore, the pounds of suspended solids leaving the activated sludge process consists of pounds of activated sludge wasted

per day and the pounds of activated sludge or secondary effluent solids discharged per day (Equation I.6).

$$\begin{aligned}&\text{pounds of suspended solids leaving the activated sludge process}\\&\quad=\text{wasted sludge (mg/l)}\times\text{wasted flow rate (MGD)}\\&\qquad\times 8.34\,\text{pounds/gallon of wastewater}+\text{secondary effluent solids (mg/l)}\\&\qquad\times\text{effluent flow (MGD)}\times 8.34\ \text{pounds/gallon of wastewater}\end{aligned}\tag{I.6}$$

The MCRT of an activated sludge process can be calculated by dividing the pounds of suspended solids or MLSS in the activated sludge process by the pounds of suspended solids leaving the activated sludge process (Equation I.7). The MCRT is Equation I.5 divided by Equation I.6.

$$\begin{aligned}\text{MCRT}=&\ \text{suspended solids in the activated sludge process/}\\&\ \text{suspended solids leaving the activated sludge process}\end{aligned}\tag{I.7}$$

MLVSS

The mixed liquor volatile suspended solids or MLVSS represents the population size of bacteria within the activated sludge process. Volatile suspended solids are solids that burn in a muffle furnace at 550°C. Although bacteria and other organic materials, for example, grease, oils, and particulate materials, burn in the muffle furnace at 550°C, it is assumed that all volatile solids are bacteria. Therefore, an increase in volatile content of the mixed liquor suspended solids (MLSS) represents an increase in the bacterial population, whereas a decrease in volatile content of the MLSS represents a decrease in the bacterial population.

SLUDGE AGE

The sludge age is the amount of time, in days, that solids or bacteria are under aeration. Sludge age is used to maintain the proper amount of activated sludge in the aeration tanks. To calculate the sludge age, it is necessary to know the amount of suspended solids (pounds) that are in the aeration tank and the amount of suspended solids (pounds) that enter the aeration tanks daily.

To determine the pounds of suspended solids that are in the aeration tank; the pounds of mixed liquor suspended solids (MLSS) must be calculated. Therefore, the pounds of MLSS in the aeration tanks consists of the concentration (mg/l) of MLSS times the volume (MG) of the aeration tanks times the weight constant of 8.34 pounds per gallon of wastewater (Equation I.8).

$$\begin{aligned}&\text{pounds of suspended solids in the aeration tanks}\\&\quad=\text{MLSS (mg/l)}\times\text{volume of aeration tanks (MG)}\\&\qquad\times 8.34\,\text{pounds/gallon of wastewater}\end{aligned}\tag{I.8}$$

To determine the pounds of suspended solids that enter the aeration tank, the pounds of primary clarifier effluent (mixed liquor influent) suspended solids must

be calculated. Therefore, the pounds of primary clarifier effluent suspended solids consists of the concentration (mg/l) of primary clarifier effluent suspended solids times the flow (MGD) of the primary effluent times the weight constant of 8.34 pounds per gallon of wastewater (Equation I.9).

$$\begin{aligned}&\text{pounds of suspended solids that enter the aeration tanks}\\&\quad = \text{primary clarifier effluent suspended solids (mg/l)}\\&\qquad \times \text{flow of primary clarifier effluent (MG)}\\&\qquad \times 8.34\,\text{pounds/gallon of wastewater}\end{aligned} \tag{I.9}$$

The sludge age of an activated sludge process can be calculated by dividing the pounds of suspended solids or MLSS in the aeration tanks by the pounds of suspended solids that enter the aeration tanks (Equation I.10). The sludge age is Equation I.8 divided by Equation I.9.

$$\begin{aligned}\text{sludge age} = {}&\text{suspended solids in the aeration tanks/}\\&\text{suspended solids entering the aeration tanks}\end{aligned} \tag{I.10}$$

SVI

The sludge volume index or SVI of an activated sludge process is used to measure the settling character (milliliters per gram) of the mixed liquor or activated sludge. The SVI is the volume of the mixed liquor suspended solids divided by the density of the mixed liquor suspended solids.

The volume of 1 l of mixed liquor suspended solids that settles after 30 minutes in a 1-l graduated cylinder typically is used to determine the SVI. The volume of settled solids (milliliters) is divided by the concentration of the mixed liquor suspended solids (g/l) to determine the SVI (Equation I.11). Because the definition of SVI requires milliliters per gram, milligrams must be converted to grams.

$$\begin{aligned}\text{SVI} = {}&\text{volume of settled solids (ml) after 30 minutes/}\\&\text{concentration of mixed liquor suspended solids } (g/\text{l})\end{aligned} \tag{I.11}$$

Appendix II

Microscopic Techniques

GRAM STAIN

The Gram stain is perhaps the most commonly used staining technique for the identification of filamentous organisms. There are several Gram staining techniques. The modified Hücker method is used at many wastewater treatment plant laboratories. Solutions needed for the Gram stain include crystal violet, Gram's iodine, a decolorizing agent, and a counterstain or safranin.

Gram stain kits can be purchased through numerous chemical vendors. The kits contain all the Gram stain solutions in dropper bottles.

To perform the Gram stain, the following laboratory procedure is used:

1. Prepare a thin smear of mixed liquor or foam on a microscope slide and allow the smear to air dry.
2. Stain the smear for 1 minute with crystal violet. Be sure that crystal violet covers the entire area of the smear. Rinse the microscope slide with distilled water.
3. Stain the smear for 1 minute with Gram's iodine. Again, be sure that Gram's iodine covers the entire area of the smear. Rinse the microscope slide with distilled water.
4. Holding the microscope slide at a 45° angle, decolorize the slide with the decolorizing agent (95% ethanol or alcohol/acetone solution) by adding the decolorizing agent drop by drop to the smear for 30 seconds. Blot dry the microscope slide.
5. Stain the smear for 1 minute with safranin. Be sure that safranin covers the entire area of the smear. Rinse the microscope slide with distilled water and blot dry.

6. Examine the Gram stained smear under oil immersion (1000×) with bright-field microscopy. Blue bacterial cells or filamentous organisms are Gram positive, whereas red bacterial cells or filamentous organisms are Gram negative.

INDIA INK REVERSE STAIN

To perform the India ink reverse stain, the following laboratory procedure is used:

1. Mix a drop of India ink (aqueous solution of carbon black particles) or nigrosine and a drop of mixed liquor on a microscope slide.
2. Place a 22 × 22-mm coverslip over the India ink/mixed liquor sample.
3. Place a sheet of tissue over the coverslip. With a blunt object, gently press down on the coverslip to remove excess India ink and mixed liquor.
4. Observe the sample at 100× and 1000× total magnification with a phase-contrast microscope.
5. Be sure that the floc particles that are being examined are surrounded by a black field of view.
6. In "healthy" or "nutrient adequate" mixed liquor, the carbon black particles penetrate to the core of the floc particles. The penetration of the carbon black particles leaves most of the area of the floc particles black or golden brown. This is a negative reaction to the India ink reverse stain.
7. In "unhealthy" or "nutrient-deficient" mixed liquor, large amounts of insoluble stored food in the floc particles impede the movement of carbon black particles to the core of the floc particles. The lack of penetration of the carbon black particles leaves most of the area of the floc particles white. This is a positive reaction to the India ink reverse stain.

LIGHT INTENSITY

The light intensity of the microscope often must be regulated to view specimens more easily. Lower powers of magnification require less light intensity, whereas higher powers of magnification require more light intensity. Adjusting the iris diaphragm lever on the condenser of the microscope regulates the light intensity of the microscope. The condenser is located beneath the stage of the microscope. Light intensity also can be adjusted by regulating the rheostat on the lamp or light bulb.

LOW-POWER MAGNIFICATION

Low-power magnification results from the use of the 10× objective lens. The total power of magnification is the power of the objective lens (10×) times the power of the ocular lens or eyepiece (usually 10×). Therefore, low-power magnification is 100×.

METHYLENE BLUE STAIN

To more easily observe a specimen or determine the composition of floc particles methylene blue staining often is used. Adding 0.01 g of methylene blue to 100 ml of absolute alcohol makes methylene blue stain.

To perform a methylene blue stain, add a drop of methylene blue to a drop of mixed liquor on a microscope slide and stir together the methylene blue and mixed liquor. Add a coverslip, and examine the wet mount with the microscope.

NEISSER STAIN

To perform the Neisser stain the following procedure is used:

1. Prepare a smear of mixed liquor on a microscope slide and allow the smear to air dry.
2. Stain the smear for 15 seconds with fresh (refrigerated and less than 6 months old) Solution 1. Rinse the microscope slide with distilled water.
3. Stain the smear for 45 seconds with Solution 2. Rinse the microscope slide with distilled water. Blot dry the microscope slide.
4. Examine the stained smear under 1000× magnification with bright-field microscopy. Light brown to yellowish bacterial cells or filamentous organisms are Neisser negative, whereas gray-blue bacterial cells or filamentous organisms are Neisser positive.

Solution 1 is prepared as follows:

Prepare A and B separately and then mix A and B at 2:1

A	
Methylene blue	0.1 g
Acetic acid	5 ml
Ethanol (90%)	5 ml
Distilled water	100 ml

B	
Crystal violet (10% w/v in 95% ethanol)	3.3 ml
Ethanol (95%)	6.7 ml
Distilled water	100 ml

Solution 2 is prepared as follows:

Bismarck brown (1% w/v aqueous)	33.3 ml
Distilled water	66.7 ml

OIL IMMERSION

When oil-immersion magnification (100× objective lens) is used, scattering of light waves (distortion of the image) is greatly reduced by having the light waves pass

through oil rather than air. Therefore, before the 100× objective lens is "clicked" into position, a drop of immersion oil (oil of immersion) is placed on the microscope slide next to the specimen to be examined. When the 100× objective lens is "clicked" into position, the tip of the objective lens passes through the immersion oil. With immersion oil on the tip of the objective lens, light waves must pass through the oil. When oil-immersion viewing is finished, lens paper should be used to clean the oil from the tip of the objective lens.

PHB STAIN

To perform the PHB (polyhydroxybutyrate) stain the following procedure is used:

1. Prepare a smear of mixed liquor on a microscope slide and allow the smear to air dry.
2. Stain the smear for 10 minutes with Sudan Black B (IV). Add more Sudan Black B (IV) to the smear if drying occurs.
3. Stain the smear for 10 seconds with safranin O and then thoroughly rinse the slide with distilled water.
4. Blot dry the microscope slide and examine the smear at 1000× with bright-field microscopy. PHB granules appear as intracellular blue-black granules, whereas the cytoplasm appears pink or clear.

Sudan Black B (IV) solution is prepared as follows:

0.3% w/v in 60% ethanol

Safranin O solution is prepared as follows:

Safranin O, 0.5% w/v aqueous

SAFRANIN STAIN

Staining a smear of mixed liquor for 1 minute with the safranin stain that is used in the Gram stain performs the safranin stain. After 1 minute of staining, the microscope slide is rinsed with distilled water. After the stained smear is blotted dry, the smear is examined with low-power (100× total) magnification under bright-field microscopy.

SCANNING

To scan a wet mount of mixed liquor, the following laboratory procedure is used:

1. With the mechanical stage control knobs, position the microscope slide so that you can view a corner of the cover slip under low-power (100× total) magnification.

2. Adjust the light intensity with the iris diaphragm lever and begin scanning the wet mount. Under low-power magnification, the light intensity should be reduced.
3. A scan is made by moving the mechanical stage with its control knobs so you can observe the sample beneath the coverslip from corner to corner, that is, from side to side and top to bottom.

SMEAR—SLIDE PREPARATION

A smear is performed to stain specific components of the biomass, for example, filamentous organisms and floc particles, or specific cellular components such as the cell wall, cytoplasm, and storage bodies. To prepare a smear of mixed liquor or foam the following procedures are used:

Mixed Liquor

1. Place a paper towel on the work area of the laboratory table.
2. Place a clean 25 × 75-mm microscope slide on the paper towel.
3. Stir and aerate a sample of mixed liquor.
4. Using a pipette, eyedropper, or straw, place a drop of mixed liquor on the center of the microscope slide.
5. Lift one end of the microscope slide and allow the mixed liquor to spread over the microscope slide onto the paper towel.
6. Allow the microscope slide to air dry. After the microscope slide has air dried, it can be examined or stained as desired for microscopic analyses.

Foam

1. Place a paper towel on the work area of the laboratory table.
2. Place a clean 25 × 75-mm microscope slide on the paper towel.
3. Using the tip of a pipette, eyedropper, or straw, transfer some foam on the end of the microscope slide.
4. Using the end of a clean microscope slide gently spread the foam across the surface of the foam-laden microscope slide, until the foam is spread as a thin smear.
5. Allow the microscope slide to air dry. After the microscope slide has air dried, it can be examined or stained as desired for microscopic analyses.

WET MOUNT—SLIDE PREPARATION

To prepare a wet mount of mixed liquor, the following laboratory procedure is used:

1. Place a paper towel on the work area of the laboratory table.
2. Place a clean 25 × 75-mm microscope slide on the paper towel.

3. Stir and aerate a sample of mixed liquor.
4. Using a pipette, eyedropper, or straw, place a drop of mixed liquor on the center of the microscope slide.
5. Clean the surface of a 22 × 22-mm coverslip with lens paper.
6. Place the cover slip on the drop of mixed liquor in the following manner:
   a. Hold the coverslip at a 45° angle on the microscope slide between the thumb and forefinger of the dominant hand. The 45° angle should face the drop of mixed liquor.
   b. Slowly slide the cover slip toward the drop of mixed liquor, and allow the mixed liquor to spread along the edge of the cover slip.
   c. Release the coverslip and allow it to fall on the mixed liquor. No air bubbles should be trapped beneath the coverslip.
   d. Place a sheet of tissue over the coverslip. With a blunt object, gently press down the coverslip to remove any excess mixed liquor.
   e. Remove the tissue and discard it appropriately.
7. If needed, label the microscope slide with appropriate information with a wax pencil.

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Abbreviations and Acronyms

cBOD	Carbonaceous biochemical oxygen demand
coBOD	Colloidal biochemical oxygen demand
DA7	Dissolved air floatation unit
F/M	Food-to-microorganism ratio
FOG	Fats, oils, and grease
HRT	Hydraulic retention time
I/I	Inflow and infiltration
LAS	Linear alkyl sulfonate
MCRT	Mean cell residence time
MG	Million gallons
MGD	Million gallons per day
mg/l	Milligrams per liter
MLVSS	Mixed liquor volatile suspended solids
MSDS	Material safety data sheet
nBOD	Nitrogenous biochemical oxygen demand
nm	Nanometer
ORP	Oxidation reduction potential
pBOD	Particulate biochemical oxygen demand
PHB	Polyhydroxybutyrate
RAS	Return activated sludge
SBR	Sequential batch reactor
scBOD	Soluble cBOD
SOUR	Specific oxygen uptake rate
sp.	One species
spp.	Two or more species
SRT	Sludge retention time

SVI	Sludge volume index
TKN	Total Kjeldal nitrogen
TSS	Total suspended solids
WAS	Waste activated sludge
μm	Micron

Chemical Compounds and Elements

Ag	Silver
Al	Aluminum
Al_3^+	Aluminum ion (trivalent)
$Al_2(OH)_4Si_2O_5$	Kaolinite
$Al_2(OH)_2Si_4O_{10}$	Montmorillonite
$Al_2(SO_4)_3 \cdot 18H_2O$	Aluminum sulfate
B	Boron
C	Carbon
Ca^{2+}	Calcium ion
$Ca(OH)_2$	Lime
Cd	Cadmium
C_2H_5OH	Ethanol
CH_3COOH	Acetic acid
CH_3OH	Methanol
$C_6H_{12}O_6$	Glucose
$C_5H_7O_2N$	Cellular material
$C_{17}H_{35}COO^-Na^+$	Sodium stearate
Cl	Chlorine
Cl_2	Chlorine
Co	Cobalt
CO_2	Carbon dioxide
–COOH	Carboxyl group
Cr	Chromium
Cu	Copper
Cu^{2+}	Copper ion
F	Fluoride
Fe	Iron
Fe_3^+	Iron ion (trivalent or ferric ion)

$FeCl_3$	Ferric chloride
$Fe_2(OH)_2Si_4O_{10}$	Nontronite
$FeSO_4 \cdot 7H_2O$	Ferrous sulfate
H	Hydrogen
H^+	Hydrogen ion or proton
HCO_3^-	Bicarbonate alkalinity
H_2CO_3	Carbonic acid
H_2NCONH_2	Urea
H_2O	Water
H_2O_2	Hydrogen peroxide
HNO_3	Nitric acid
HOCl	Hypochlorous acid
HPO_4^{2-}	Orthophosphate
HS^-	Sulfide
H_2S	Hydrogen sulfide
I	Iodine
K	Potassium
K^+	Potassium ion
$KAl_2(OH)_2(AlSi_3)O_{10}$	Hydrous media
Mg	Magnesium
Mn	Manganese
Mn^{2+}	Manganese ion
Mo	Molybdenum
N	Nitrogen
N_2	Molecular nitrogen or dinitrogen
Na	Sodium
Na^+	Sodium ion
$NaSO_3$	Sodium sulfite
$–NH_2$	Amino group
NH_4^+	Ammonium ion
N_2H_4	Hydrazine
NH_2CH_2COOH	Glycine
Ni	Nickel
Ni^{2+}	Nickel ion
NO_2^-	Nitrite ion
NO_3^-	Nitrate ion
N_2O	Nitrous oxide
O	Oxygen
O_2	Oxygen or dissolved oxygen
–OH	Hydroxyl ion
P	Phosphorus
Pb	Lead
–POOH	Phosphoryl group
S	Sulfur
Se	Selenium
–SH	Thiol group
Si	Silica
SO_3^-	Sulfite

SO_4^{2-}	Sulfate
–SOOH	Sulfhydryl group
V	Vanadium
Zn	Zinc
Zn^{2+}	Zinc ion

Glossary

absorb Penetration of a substance into the body of an organism

acclimate Gradual repair or replacement of enzymes or cellular materials damaged by inhibitory compounds

adsorb The taking up of one substance at the surface of an organism

agglutinate Bonding or joining together of bacterial cells to form a floc particle

alkalinity Having a pH greater than 7

amine The nitrogen and hydrogen group, $-NH_2$

amplifier A treatment unit or tank, such as the aeration tank, in which bacteria increase in number through the degradation of BOD

anaerobic An environment in which free molecular oxygen is not used by bacteria for the degradation of BOD

anion A negatively charged ion such as nitrate, NO_3^-

anoxic An environment in which bacteria use nitrite ions or nitrate ions for the degradation of BOD

binome The scientific name of an organism, for example, *Sphaerotilus natans*. The name consists of the genus (*Sphaerotilus*) and species (*natans*) of the organism

bioaugmentation The addition of commercially prepared cultures of organotrophic bacteria and nitrifying bacteria to a wastewater treatment process to improve operational conditions

biological holdfast A series of lacelike treads providing fixed film bacterial growth that is immersed in a suspended growth system or activated sludge process

biomass The quantity or weight of all organisms within the treatment process

bright-field A microscope that provides a bright or highly illuminated field of view or viewing area

carbonaceous A compound that is organic or contains carbon and hydrogen

cation A positively charged ion such as ammonium, NH_4^+

cellulose A polysaccharide consisting of numerous glucose molecules linked together to form an insoluble starch

cirri The ring of cilia around the mouth opening of stalk ciliated protozoa

coagulant A metal salt such as ferric chloride that is used to capture, dewater, or thicken solids

congealed Pulled together tightly

cuticle A deposit of waterproof, waxy material forming the external layer of free-living nematodes, flatworms, and bristleworms

cytoplasm The jellylike internal content of the cell

denitrification The use of nitrate ions or nitrite ions by bacteria for the degradation of cBOD. The degradation results in the release of the insoluble gases molecular nitrogen and nitrous oxide

duckweed The smallest flowering plant. The plant produces a white flower and floats on the wastewater with its "root" system suspended beneath its leaves. The nitrogen nutrient for duckweed is the nitrate ion.

endogenous The degradation of internal reserve substrate

enzyme A proteinaceous molecule found inside a cell or released by a cell that expedites the rate of a biochemical reaction without being consumed in the reaction

exocellular Found outside the cell

exponential A stage of growth occurring in populations of unicellular organisms during which the logarithm of the cell number increases linearly with time, for example, 1, 2, 4, 8, . . .

facultative An organism that has the ability to use free molecule oxygen or another molecule such as nitrate ions or sulfate ions to degrade cBOD

fibril A small (2–5 nm) extension of the cell membrane that protrudes through the cell wall to the bulk solution. The fibril contains chemical groups that are negatively charged and provide for the flocculation of bacteria and adsorption of fine solids.

filtrate The liquid and its contents that pass through filter paper

free-living nematode A microscopic nonsegmented worm that does not cause disease. The worm is found in soil and water and is washed into the activated sludge process through inflow and infiltration.

generation time The time required for the cell population or biomass to double

genus A taxonomic or classification group of organisms above the species level that share many features

immiscible The property of two or more liquids not mixing and forming more than one phase when brought together

inert Not readily changed by chemical means

infiltration Groundwater that enters the sewer system through cracks in laterals, mains, and manholes

inflow Storm water that enters the sewer system through catch basins and downspouts

interface Sharp contrast boundary between two phases, either or both of which may be solid, liquid, or gas

intracellular Within the cell

ion Any atom or molecule that has an electric charge caused by the loss or gain of an electron

leachate The liquid stream that is released by pressure or gravity from solids

lorica The protective translucent covering found on some rotifers

lysis To break open; namely, on the death of bacterial cells, the content of the cells is released to the environment

methanogen Methane-forming bacteria. Bacteria that produce methane from simplistic soluble cBOD such as acetic acid

morphologic Structural form, feature, or characteristic

multivalent A negative or positive ion with a charge greater than 1

myoneme The contractile filament in stalk ciliated protozoa that permits the protozoa to spring

nitrogenous Nitrogen-containing compounds

Nocardioforms A group of highly branched and specialized bacteria that produce viscous chocolate brown foam in the activated sludge process

organic-nitrogen Compounds that contain carbon, hydrogen, and nitrogen, for example, urea (H_2NCONH_2)

organotroph An organism that obtains its carbon and energy from the oxidation of cBOD

oxidation The biological or chemical addition of oxygen to a compound

phase contrast A microscope that provides a light source that strikes the specimen to be viewed at different phases. The light permits the specimen to be in sharp contrast to its surrounding environment. Phase contrast reduces the need for microbiological staining techniques to view a specimen.

phenol Carbolic acid, C_6H_5OH, chief constituent of coal tar

polysaccharide A complex carbohydrate such as cellulose or starch

proteins A class of high-molecular-weight polymers composed of amino acids joined by peptide linkages

quiescent Quiet, not turbulent

redox The measurement of the amount of oxidized compounds and reduced compounds in an environment

reduction The addition of electrons to a compound; the removal of oxygen

substrate Food or BOD

***t*-butanol** A four-carbon alcohol that contains the hydroxyl group (–OH) on the first or fourth carbon

unicellular Having one cell

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