BIOLOGICAL WASTEWATER TREATMENT PRINCIPLES

GENERAL OVERVIEW

Natural receiving waters including rivers, streams, and tidal areas sustain a background population of microorganisms including bacteria, fungi, and algae. These organisms require energy for respiration and organic carbon food sources in order to synthesize new cells using the following general equation:

$$\text{MICROBES} + \overset{\text{ORGANIC}}{\text{FOOD}} + \text{NUTRIENTS} + \text{OXYGEN} \rightarrow \overset{\text{MORE}}{\text{MICROBES}} + \overset{\text{CARBON}}{\text{DIOXIDE}}$$

In the above equation, the microbes occur naturally and consume organic food sources that are naturally present in the water. Some of the carbon matter in the food is biodegraded to release energy that drives the reaction. Energy is released through the biodegradation process by combining part of the organic food source's carbon compounds with oxygen. The byproducts of this reaction are additional microbial cells and carbon dioxide. Nutrients, primarily nitrogen and phosphorus, complete the reaction and are needed as part of the building blocks used to form new microbial cell tissue.

In a clean water environment, the amount of available organic food supplies are limited. This places a restriction on how fast the above reaction proceeds and also on how many microbes are able to grow. In general, the population of microbes in a clean water environment is restricted to a low background level by the limited amount of organic food that is present. While periodic fluctuations in the food supply may cause brief periods of population swings or declines, the number of microbes in the ecosystem will achieve an equilibrium condition over time that is based on the steady state amount of organic food present.

If an artificial organic food supply is allowed to enter the ecosystem, the number of microbes that can be sustained will increase in response to the added food. If the amount of additional food is large, the population of microbes may increase exponentially and will continue to grow up to the point that the amount of food again becomes limiting for the elevated population.

Raw sewage contains a high organic carbon content that provides an excellent supply of food for waterborne microbes. If raw sewage is discharged into a receiving water, the bacteria population will become elevated in response to the new addition of food. This causes the above biodegradation reaction to proceed rapidly and, in the process, to create larger amounts of new microbes and carbon dioxide. This requires that more oxygen be available for use by the microbes. If sufficient extra food is added by the sewage discharge, the population of microorganisms and the resulting oxygen consumption may proceed so rapidly that all of the receiving water's oxygen is depleted.

The maximum amount of dissolved oxygen present in a receiving water is a function of temperature, atmospheric pressure, elevation, the solids content of the water, and salinity. In any case, the saturation value of dissolved oxygen that is present is relatively small as shown below in Table 8. At sea level and 0°C, the maximum amount of dissolved oxygen that can be saturated into solution is 14.6 mg/l. This value decreases to only 7.6 mg/l at 30°C. For this reason, there is less dissolved oxygen available in the summer when water temperatures are warmer than during the cold winter months. Unfortunately, high water temperatures will also stimulate microbial activity which will cause biodegradation reaction rates to increase and oxygen depletion to occur faster. This makes summertime the most critical period for maintaining dissolved oxygen conditions in receiving waters. Table 8 also shows the effect that salinity has on dissolved oxygen levels. As a receiving water becomes higher in chlorides, less oxygen can be dissolved into the water.

TABLE 8:

SATURATION VALUES OF DISSOLVED OXYGEN IN WATER

TEMPERATURE (0°C)	DISSOLVED OXYGEN IN FRESH WATER (mg/l)	DISSOLVED OXYGEN IN SALT WATER (mg/l)
0	14.6	13.0
5	12.8	11.4
10	11.3	10.1
15	10.2	9.1
20	9.2	8.3
25	8.4	7.6
30	7.6	6.9

If free dissolved oxygen is present, the ecosystem is considered to be aerobic. If excess raw sewage is discharged to a receiving water, the available food supply may result in a large microbial population that fully depletes all of the dissolved oxygen. This results in the system becoming anoxic or anaerobic. Since most fish and aquatic species require a minimum dissolved oxygen level of at least 5.0 mg/l to survive, the depletion of all the dissolved oxygen is a serious environmental concern. Septic conditions also present a variety of other environmental problems including odor generation, acidic compound formation and pH drops, lethal gas generation, and explosive environments.

The origin of these septic system issues can be reviewed by considering the data shown on Table 9. Microbes in the ecosystem can use other oxidizing compounds besides oxygen in the biodegradation reaction. Other suitable oxidizing agents include nitrate, sulfates, and carbon dioxide. Bacteria prefer to use oxygen because more energy is released than if other compounds are used. This energy allows the bacteria to degrade the food supply more completely and at a faster rate. The carbon dioxide that is released as a byproduct is natural to the environment and innocuous. Should all of the oxygen be depleted, other types of microbes will take over the system and use other compounds to degrade the organic matter. These alternative reactions result in less energy being released which slows down the treatment reaction rate or results in less complete treatment in the same reaction time. As shown in Table 9, some of the by-products produced by these alternative reactions are less desirable than the carbon dioxide produced when oxygen is used:.

TABLE 9:

ORGANIC BIODEGRADATION REACTION PRODUCTS

TYPE OF SYSTEM	OXIDIZING COMPOUND	UNIT ENERGY RELEASED (Kcal/mole)	BYPRODUCTS FORMED	ISSUES WITH BYPRODUCTS
Aerobic	Oxygen	25.3	Carbon dioxide	None
Anoxic	Nitrate	23.7	Nitrogen gas	Rising solids
Anaerobic	Sulfate	1.5	Hydrogen sulfide	Odorous, Corrosive, and Toxic
Anaerobic	Carbon Dioxide	0.9	Methane	Odorous, Explosive, and Toxic

Oxygen is the oxidizing agent of choice in microbial biodegradation because it results in high energy yields and harmless byproducts. Nitrate results in nearly the same energy yield, but produces nitrogen gas that can float solids in receiving waters or treatment systems. Sulfur or carbon dioxide compounds can be used to biodegrade organic matter under septic conditions; however, extremely low energy yields result and hydrogen sulfide or methane gas is produced. These gases are odorous, corrosive, explosive, and toxic. They contribute to acid formation and pH reductions as well as unsafe environmental conditions. Bacteria in the ecosystem will always use oxygen first if it is available and, in doing so, will avoid the types of adverse byproducts shown in Table 9. Should all of the oxygen be depleted, the ecosystem will continue to biodegrade the organic food supply by converting to an anoxic or anaerobic environment. In these cases, adverse environmental effects will be created.

The discussion on microbes up to this point has focussed on naturally occurring bacteria and other microorganisms that are simply biodegrading organic compounds. It is important to note that raw sewage discharges into a receiving water also present additional problems from harmful human enteric microbes, called pathogens, that can spread waterborne diseases to humans. The wastewater discharge from a community will contain a representative sampling of all diseases that exist within the general population of sewer users. The presence of these diseases is usually assessed by measuring the amount of E. coli or fecal coliform bacteria that are present in the raw sewage. These organisms serve as indicators of upstream human waste contamination. If the indicator organisms are present, it can be assumed that harmful disease causing pathogens are also present. Given the possibility of downstream human contact or shellfish contamination, the presence of pathogens in a raw sewage discharge represents a serious environmental health concern.

As previously discussed, wastewater discharge licenses limit the amount of pollutants that can be discharged into the environment. Maximum discharge limits are established for total suspended solids (TSS), biochemical oxygen demand (BOD) and E. coli. The purpose of these limits is to accomplish the following objectives:

- Limit the amount of available organic matter that is discharged to the receiving water to avoid overstimulating the growth of microorganisms in the environment.

- Limit the amount of dissolved oxygen that the discharged organic matter will deplete in the environment as it is biodegraded by naturally occurring bacteria.

- Disinfect the wastewater discharge to protect human health by reducing the number of pathogens in the water.

Wastewater collection systems are designed to convey raw sewage to a central location for treatment. Wastewater treatment plants are designed to process the raw sewage prior to its discharge to reduce its organic content, oxygen demand, and pathogenic content. This is accomplished by utilizing treatment processes that remove the waterborne pollutants directly (primary treatment) or that convert them into bacterial cells (secondary treatment). With biological treatment processes, the same organisms that occur naturally in the environment are grown under controlled conditions in the treatment plant. They are allowed to eat the organic portion of the incoming sewage which leaves clean water behind. Clean water is then discharged into the environment and the plant's excess cells, called sludges, are disposed of in an environmentally acceptable manner. By the time that the treated effluent is discharged, it has lost its ability to serve as a food supply for the receiving water's microbes.

A wastewater treatment plant consists of a series of unit processes that receive polluted raw sewage directly from the sewer system and progressively clean it to a point that it can be safely discharged to a receiving water. Figure 3 shows the typical progression of unit processes in a wastewater treatment plant. Raw sewage first enters the headworks of the plant and is treated in several preliminary treatment processes that remove debris and make the water easier to treat in subsequent downstream processes. Primary treatment follows preliminary treatment and includes sedimentation processes that allow the water to be held under quiescent conditions. Settleable pollutants fall to the bottom of the primary treatment reactors and form sludges. The clarified primary effluent then flows into secondary treatment where microbes are grown to biodegrade non-settleable organic pollutants. Effluent from the secondary treatment system is further treated in a disinfection process to remove pathogens. Sludge residuals that form in each unit process must also be treated and properly discharged of at licensed sludge processing facilities.

PRELIMINARY TREATMENT PROCESSES

Preliminary treatment systems encompass all unit processes in the headworks of a treatment plant prior to primary treatment. The purpose of these processes is to refine the incoming wastewater’s characteristics to make the water more conducive to treatment in downstream processes. Preliminary treatment is also designed to remove undesirable pollutant constituents and debris from the influent to prevent it from interfering with downstream treatment systems and to protect subsequent equipment from damage. Typical preliminary treatment processes include screening, shredding, grit removal, equalization, and pH neutralization. Screening and shredding processes either remove or refine incoming wastewater solids to achieve a uniform particle size which can be more efficiently handled by downstream treatment systems. Poor screening or shredding may lead to plugging problems in downstream processes, pumps, or piping. Grit removal systems remove abrasive substances from the wastewater such as sand and gravel. Inadequate grit removal can lead to excessive pump and impeller wear, equipment abrasion, pipe deterioration, and loss of available treatment tank volumes. Equalization is used to reduce the variability of erratic waste loads by providing upstream storage of influent flows. Effective equalization can dampen influent flow, TSS, and BOD fluctuations, minimize pH and temperature

Figure 3

variability’s impacts on the treatment plant, and result in controlled loadings to the downstream processes. Where influent loadings exhibit a high degree of hydraulic or pollutant variability, inadequate equalization can result in unstable downstream performance, particularly in biological treatment systems. Neutralization processes are used to chemically alter the influent pH by the addition of acid or alkaline compounds and is required when the pH of wastewater is highly variable or outside a required regulatory or process range. Inadequate neutralization can result in pH swings in downstream processes effecting their efficiency and performance. In addition to these systems, preliminary treatment processes also include other typical headworks functions such as flow measurement and wastewater sampling equipment. These systems are used to monitor the incoming waste’s characteristics for regulatory and process control purposes.

While preliminary treatment processes are conceptually simple in function and operation, the important role that these processes play in overall treatment plant optimization is often ignored. Since the sole purpose of preliminary treatment is to make the wastewater easier to treat, marginal process performance of existing preliminary systems, or the omission of critical preliminary treatment processes from a plant’s headworks, almost always results in a loss of downstream process efficiency and stability.

Preliminary treatment processes are relatively simple to operate. Key factors in keeping typical preliminary treatment equipment operating at maximum efficiency include:

- Grit systems should be adjusted in response to changes in the incoming flow rate. Higher wet weather flows will tend to produce more grit than lower dry weather flows. The aeration rate into an aerated grit chamber should be adjusted in response to changing flow rates and grit production amounts. Once settled, grit should be removed from the system frequently to prevent it from becoming compacted or septic.

- Grinder equipment should be kept in a well maintained condition. Cutter and shredder blades should be kept sharp.

- Flow metering equipment should be frequently checked and calibrated to make sure that it is providing accurate readings.

- Sampling equipment should be properly maintained, frequently calibrated, and cleaned often to prevent the fouling of sample tubing that can lead to contaminated, false samples and test results which are not representative.

- All debris removed from the headworks area, such as gravel, sand, screenings, and other materials should be disposed of frequently to prevent odors and nuisance conditions from forming in the plant.

PRIMARY TREATMENT PROCESSES

The purpose of all wastewater treatment plant processes is to separate solids from raw wastewater such that the clarified flow stream may be discharged into a receiving water with minimal adverse environmental impacts. Wastewater solids occur in a variety of forms including discrete large particles, smaller suspended solids as measured by the TSS test, and non-settleable colloidal or dissolved solids. Different treatment plant unit processes are designed to target a specific category of solids for removal. The preliminary treatment processes previously discussed remove discrete, large solids such as debris and grit. Non-settleable, biodegradable colloidal or soluble solids are removed in secondary treatment processes, such as Brewer's activated sludge system, by allowing these materials to be biologically converted into microbial cells, than subsequently settled and removed in the final clarifiers.

Primary treatment represents an intermediate process step between preliminary and secondary treatment in which solids of sufficient density settle by gravity under the quiescent conditions provided in primary clarifiers. By providing a settling tank with reduced velocities, a significant portion of the waste's influent TSS, normally fifty to seventy percent, will settle under the influence of gravity to become raw primary sludge. Since the removal of organic solids reduces the organic content of the wastewater for later bacterial biodegradation, primary treatment also reduces the BOD of the influent, often by twenty-five to forty percent.

A significant advantage of removing solids in a primary clarifier instead of in downstream secondary processes is that gravity separation is far less expensive than biological removal. In a primary clarifier, the only mechanical systems utilized are scrapers for removing settled sludge or floating solids. Secondary treatment systems generally require aeration equipment, sometimes chemical feed systems, and substantially more process control monitoring. Solids removed as primary sludge are much easier to dewater than the waterlogged microbial cells that constitute secondary sludges. However, primary sludges have the potential of creating more nuisance conditions and odors that secondary sludges since they represent raw wastewater solids with a high organic content and without prior biological stabilization.

Unlike more complex secondary treatment systems, primary treatment processes have only limited adjustments that can be manipulated by the operators. Once the capital infrastructure for the primary treatment system is in-place, the operator's only process control option is to alter the rate of sludge removal from the bottom of the clarifier. It is important to remove the settled sludges in a timely manner to minimize the formation of septic sludges and odorous gases.

The solids removal efficiency of a primary clarifier can be measured by the following equation:

If the influent solids concentration is compared to the effluent solids concentration, efficiency of the reactor can be calculated. The efficiency of a primary clarifier is effected by several factors including:

- The amount of water applied to the clarifier's surface in gallons per day per square foot of area. This is referred to as the clarifier's surface overflow rate or hydraulic loading rate. As the rate of flow to the clarifier is increased, its efficiency will be reduced. The surface overflow rate can be calculated as follows:

$$\boxed{\text{SOR} = \frac{Q}{A}}$$

where SOR = clarifier surface overflow rate in GPD/SF (gallons per day per square foot).

Q = flow applied to the clarifiers in gallons per day (GPD).

A = area of clarifier surface on-line in square feet (SF).

- The length of time that the wastewater remains in the clarifier under quiescent conditions will impact its treatment performance. If the water is held too long, it will become septic and some of the settled raw sludge may rise again due to the formation of gas bubbles from anaerobic conditions in the sludge blanket. If the detention time of the clarifier is too short, the pollutants will not have sufficient time to settle and will be washed through the primary treatment process. The detention time of a primary clarifier can be calculated from the following equation:

where θ = detention time of the clarifier in hours

V = volume of the clarifier in MG (million gallons).

Q = flow through the clarifier in MGD (million gallons per day).

- The rate at which sludge is removed from the clarifier will also impact its efficiency. The operator must operate the raw sludge pumps in a manner that seeks an equilibrium point at which enough holding time is maintained to thicken the settled sludge while not making the holding time so long that septic conditions develop. Typically, a one hour holding time is considered sufficient for primary sludge. The sludge pump should be operated either continuously or on a timer that is activated at least every hour. It is important to note that deep sludge blankets are subject to washout during peak flow periods which can cause excessive pollutant carryover to reach downstream processes.

Table 10 summarizes some of the typical target values that are considered normal for optimized primary treatment processes. As discussed, TSS removal efficiencies should be between 50 and 70 percent. BOD removal efficiencies should be between 25 and 40 percent. Surface loading rates should typically be between 800 and 1200 GPD/SF for municipal wastewater and between 700 and 800 GPD/SF for Eastern’s whitewater at average daily flow loadings. During peak hourly flows conditions, the clarifiers may be loaded at a surface overflow rate of 2000 to 3000 GPD/SF. The detention time of the primary clarifiers should be between 2.0 and 3.0 hours at average daily flow conditions and between 1.0 and 1.5 hours at peak hourly flow conditions.

TABLE 10: TYPICAL PRIMARY TREATMENT PERFORMANCE STANDARDS

DESIGN PARAMETER	TYPICAL VALUE
TSS Removal Efficiency	50 – 70 %
BOD Removal Efficiency	25 – 40 %
Surface Overflow Rate (SOR)	
Average daily municipal	800 – 1200 GPD/SF
Average daily industrial	700 – 800 GPD/SF
Peak hourly	2000 – 3000 GPD/SF
Detention Time (θ)	
Average daily	2.0 – 3.0 hours
Peak hourly	1.0 – 1.5 hours

BIOLOGICAL TREATMENT PROCESSES

The same naturally occurring microbes that are present in the receiving water can be grown in a treatment plant to stabilize wastewater. The objective of a biological wastewater treatment plant is to force the plant's organisms to biodegrade all of the raw sewage's organic pollutant content prior to its discharge as treated effluent. Raw sewage represents an excellent medium in which to grow bacteria and microbes. It has a high biodegradable organic content and is also rich in nutrients. If oxygen is added to the system, all of the conditions needed to grow bacteria are present.

The overall microorganism population in a treatment plant secondary aeration reactor contains numerous types of species and microbes. Bacteria are the primary workers in a wastewater treatment plant. They feed on the wastewater pollutants and biodegrade them into stable end-products. Many different types of bacteria may be present, each with the ability to decompose specific types of pollutants. This allows many different types of organic compounds to be simultaneously treated in a biological system.

The rate at which the bacteria grow is a function of how much food is present in the treatment reactors. Since the BOD of a wastewater can be considered to be an indication of its biodegradable organic content, the amount of available food can be approximated by the mass of BOD in lbs/day that enters the treatment reactor. The amount of bacteria in the treatment system is often estimated by measuring the suspended solids content of the plant's aeration system. These solids are called mixed liquor and their solids content is called the mixed liquor suspended solids (MLSS). Often, the organic portion of the MLSS is estimated by measuring the volatile or combustible portion of the MLSS in a muffle furnace. This value is referred to as the mixed liquor volatile suspended solids (MLVSS). By relating the amount of incoming food (F) to the amount of microbes held in the treatment reactor (M), an assessment can be made of how the food supply compares to the plant's biological population. This will, in turn, allow an assessment to be made of the bacteria's expected growth rate.

The food to microorganism ratio (F/M) of a treatment system relates the amount of available food to the population of microbes under aeration as follows:

$$\frac{F}{M} = \frac{\text{LBS/DAY OF INFLUENT BOD INTO AERATION}}{\text{LBS MLVSS UNDER AERATION}}$$

In a treatment reactor with a high F/M greater than 0.50, bacterial growth will be rapid and exponential. This type of growth will be classified as log growth and treatment plants operated in this manner are called high rate plants. Log growth is achieved when a large food supply is present for a small amount of microbes.

If the MLVSS population is allowed to grow and increase, more moderate F/M values of 0.20 to 0.50 will be achieved. In this mode, the bacterial population is considered to be well balanced with the available food supply. Growth rates will be stable and are referred to as exhibiting declining growth. Treatment plants operated in this manner are called conventional plants.

If large MLVSS populations are allowed to develop to levels well in excess of the available food supply, low F/M values of 0.20 or less will occur. In this mode, the plant's bacteria find themselves in a starvation mode. They are forced to biodegrade some of their own cell mass simply to respire. Over time, the bacteria population will decline. This level of growth rate is called endogenous decay and plants operated in this starvation mode are called extended aeration processes.

As will be discussed, the bacterial growth rate of a treatment system, and the F/M at which the plant is designed and operated, play an important role in the level of wastewater treatment that will be achieved. As will also be discussed, the BOD test required to calculate an F/M ratio takes five days to yield results. Because of the operational importance of understanding a plant's F/M ratio at any given point in time, an alternative method of inferring the F/M from rapid solids testing data has been developed. It can be shown that, for a given range of food supply reaching the plant, the F/M ratio occurs as the result of how many microbes are present in the system. If the operator holds a low mass of microbes in the system, the plant's MLVSS will remain relatively young and the microbial population will be low yielding a high F/M. If large amounts of MLVSS are held in the system, an old sludge will develop and the large microbial population will yield a low F/M. This gives rise to the concept of a plant's sludge age.

As will be shown later, the age of the sludge held in a treatment plant can be measured in just a few hours, as compared to the five day BOD test, and quickly related to the F/M. An operator can create a high F/M by keeping the MLVSS at low concentrations at a young sludge age. Generally, this occurs at a sludge age of two to four days. This mode of operation is typical of a high rate plant in the log growth phase.

A plant can achieve a moderate F/M by keeping a balanced population at a moderate sludge age of four to twelve days. This mode of operation is typical of a conventional plant operating in a declining growth phase.

A plant can achieve a low F/M by keeping a large amount of old sludge in the system with a sludge age of twelve to thirty days. This mode of operation is typical of an extended aeration plant operating in a zone of endogenous decay.

The age of a treatment reactor's sludge is defined as the average number of days that a typical bacterial cell in the MLSS can be expected to survive in the system. It is commonly measured by the Mean Cell Residence Time (MCRT) test which is defined as follows:

$$\boxed{\text{MCRT} = \frac{\text{lbs MLSS held under aeration}}{\text{lbs/day of TSS lost from system}}}$$

As will be discussed, a treatment plant's operator can adjust the amount of solids held under aeration and lost from the system by changing the amount of bacteria wasted from the facility each day. This has the effect of adjusting the plant's F/M and of defining how the bacteria in the plant will grow and settle.

The above discussion on bacterial growth, F/M rates, sludge age, MCRT, growth rates and treatment process classifications is summarized below in Table 11:

TABLE 11:

SUMMARY OF BACTERIAL GROWTH RATE PARAMETERS

PARAMETER	HIGH RATE PLANT	CONVENTIONAL PLANT	EXTENDED AERATION PLANT
Bacterial growth rate mode	Rapid	Slow	Starvation
Growth rate classification	Log growth	Declining growth	Endogenous Decay
Typical F/M range	> 0.50	0.20-0.50	<0.20
Type of MLSS sludge	Young	Moderate	Old
MCRT (days)	2-4	4-12	12-30
Process condition	Much food for few microbes	Balanced food supply for microbes	Many microbes but little food

In subsequent discussions, the significance of the data presented in Table 11 to the expected performance of the treatment plant will be reviewed.

MICROSCOPIC ANALYSIS OF MIXED LIQUOR

The daily observation of the types of microbes present in a plant's MLVSS gives an important indication of not only the system's F/M and MCRT, but also the expected effluent quality as well. It is difficult to observe bacteria using the types of microscopes that are realistically available in a municipal treatment plant. However, larger life forms that are readily observed can be related to the amount of bacteria that is present. These life forms include one-celled amoebas, flagellates, free swimming ciliates, stalked ciliates, rotifers, and nematodes. All of these animals utilize bacteria as their food supply. Their presence can be related to the amount of bacteria present which, in turn, can be related to the amount of food or BOD available in the system. Each of these organisms can be seen in Figure 4. These microbes are further described as follows:

- Amoebas are single-celled microbes that represent the lowest known animal life form. They have a non-rigid wall that contains pseudopods or "fake feet" that can reach out and entrap bacteria. They cannot swim for food, so they rely on having a large supply of bacteria present in order to survive. If a large number of amoebas are seen under the microscope, it can be assumed that a large bacterial population is present and supported by a high BOD in the system. The plant's MLSS is likely young, the F/M is high, and the MCRT is low. The water in the treatment plant will be found to be very polluted with a large amount of organic matter present.

Figure 4 – Typical MLSS Microbes

- Flagellates are slightly more advanced animals than amoebas. They have a poorly developed tail, called a flagella, which allows them to move slowly through the water to search for food. While they need a smaller supply of bacteria to graze upon as a result of their ability to swim in search of food, they still require a relatively large bacteria population to sustain their ineffective method of movement. When large numbers of flagellates are present under the microscope, this indicates that a large number of bacteria are also present in the MLSS. A high BOD level is needed to sustain these bacteria so the plant is still in a high F/M and low MCRT mode with a young sludge age. The water in the plant will be found to be relatively polluted with a high amount of organic matter present.

- Free swimming ciliates under the microscope are a sign of a maturing treatment plant. These animals are surrounded by ciliated hairs that give the organism great mobility to swim around in search of food. Because the ciliates can travel to the food supply, it is not necessary to have as high a concentration of available BOD organics as was the case with the amoebas or flagellates. The presence of large amounts of free swimming ciliates suggests that the plant's water is becoming clean, that the BOD supply is declining, and that the number of bacteria in the water needed to feed the ciliates has also declined. This is typical of a moderate F/M and a moderate MCRT. The food supply into the system is becoming balanced with the amount of bacteria in the MLVSS.

- Stalked ciliates represent the next progression to a clean water environment and a maturing treatment system. They consist of protozoa with a long stalk that attaches to surfaces in the plant's MLSS contents. They have no cilia for swimming and their appearance suggests that there is not enough food energy left in the plant to support the activity of the free swimming ciliates. As stalked ciliates become predominant, this is a sign that much of the food in the water has been consumed and, as a result, the bacteria supply needed to feed the stalked ciliates has also been diminished. This is a sign of a decreasing or moderate F/M and MCRT plant. It should consist of a healthy MLVSS population living in clean water.

- Rotifers are very advanced, multicellular organisms that appear only in very clean water. They need only a small amount of bacteria to survive and occur in large numbers only when the plant's MLSS bacteria have eaten most of the organic matter in the water and have began to decline in numbers themselves. The presence of a large predominance of rotifers suggests that the MLSS has been held for a very long time such that very little BOD is left in the system. They are the sign of an old sludge with a high MCRT and a low F/M.

- Nematodes are large worms that generally live only in old sludges and sediments that are surrounded by clean water. They are the sign of a very old sludge and extremely high MCRT and low F/M levels. At the point that nematodes appear, very little organic matter or BOD, and few bacteria, are present in the plant.

In any given biological treatment process, all of the above animals may be present under the microscope at different times or in different concentrations. What is important in conducting a microscope analysis of the MLVSS is to establish which microbes appear to be most plentiful or predominant. Changing trends of relative predominance over time are often more significant than the specific predominance on any one given day. As shown in Figure 5, the type of predominant animal viewed under the microscope can be related to the amount of bacteria in the system. The level of bacteria can then be related to the amount of food (BOD) that remains in the water over time. This allows the plant operator to infer an F/M, an MCRT, and a sludge age simply by conducting a brief daily microscopic analysis of the mixed liquor which will reveal a wealth of information to the operator on the health of the MLSS, the efficiency at which the plant is operated, the degree of waste stabilization that is occurring and the overall performance of the treatment plant.

ACTIVATED SLUDGE BIOLOGICAL TREATMENT PROCESSES

The activated sludge process is the most common method of providing biological wastewater treatment for municipal sewage. Its goal is to develop and maintain a large population of microbes under aeration in a four-part treatment process as shown in Figure 6. Bacteria are grown in an aeration basin and feed on the incoming organic pollutants thereby removing the pollutants from the water. The four major process components of an activated sludge system are as follows:

1) An aeration basin is used to breed and grow a large bacterial population to feed on the incoming wastes. The aeration basin is supplied with a steady supply of dissolved oxygen to keep the biodegradation process aerobic. If needed, supplemental nitrogen and phosphorus nutrients can also be added, although raw sewage usually contains an ample amount of nutrients. The aeration basin must be provided with a sufficient detention time to allow the wastewater organics to be fully assimilated into the microbes. By the time that the wastewater leaves the aeration basin, all incoming organic matter

Figure 5 – animal population shifts

Figure 6 – activated sludge process

(BOD) should have been converted into either bacterial cells (MLVSS) or given off to the atmosphere as carbon dioxide.

2) A final clarifier is used to separate the bacterial cells in the MLSS from the water that carries them. The clarifier is a large reactor that holds the aeration basin's effluent for periods of two to three hours. This allows the MLSS cells to settle to the bottom of the clarifier leaving clear water behind. The clear water can be discharged to the receiving water after proper disinfection while the settled cells can be further processed. At the point at which the cells are settled, they are referred to as activated sludge.

3) A return sludge pump is used to return the settled activated sludge cells from the final clarifiers back to the aeration basin. Here, they will be incorporated into the MLSS and will be allowed to treat additional incoming BOD. The sludge that is recycled is referred to as return activated sludge (RAS) and it is conveyed through the system using an RAS recycle pump. Over time, the return of the activated sludge allows the operator to retain bacterial cells in the system for periods of time far in excess of the hydraulic detention time of the plant. In theory, cells can be held in the plant for indefinite sludge age periods depending on the amount of sludge that is returned.

4) A waste sludge pump is added to the system in recognition of the fact that returning all of the sludge in the plant will eventually cause the aeration basin's MLSS level to increase to unacceptable concentrations. All treatment plants operate best at specific MLSS, MLVSS, F/M, MCRT, and sludge age ranges that produces the best effluent at that plant. The operator uses the waste sludge system to maintain the process at optimal microbial levels by bleeding off excess MLSS cells on a periodic basis.

In order for the activated sludge process to produce an acceptable quality effluent, each of the above four unit processes must be optimized and be working together as a unified system. The plant operators must utilize a proactive process control strategy to create an environment that promotes good biological growth. The activated sludge process will produce an excellent quality effluent when the following four conditions occur:

- The environment in the aeration basin must be regulated to cause the microbes in the MLSS to assimilate the influent BOD into their cells and to convert the organic content of the sewage into either carbon dioxide or new cells.

- The type of new microbial cells produced must be conducive to flocculation and good settling in the final clarifiers. It does no good to assimilate the incoming BOD into the MLSS cells in the aeration basin if the cells that are created will not settle in the final clarifiers. Good settling MLSS will occur only if many process parameters in the plant are optimized. These parameters include F/M, MCRT, pH, dissolved oxygen, nutrients, and numerous other factors. Most activated sludge plants that cannot produce a clean effluent do so as the result of their inability to produce a sludge that will settle in the clarifiers. In this case, most of the incoming pollutants have been removed into the MLSS cells, but the clarifiers cannot remove the MLSS cells from the water. Unfortunately, DEP and EPA discharge licenses for BOD and TSS do not distinguish between raw pollutants and washed out mixed liquor cells. A plant is subject to license violations and enforcement action if it cannot yield a good settling sludge in the clarifiers. The development of a properly settling activated sludge is one of the highest priorities for the operators of the facility.

- The rate at which the return sludge is sent back to the aeration basin from the final clarifier helps to determine the vitality of the sludge and its concentration. Sludge held too long becomes septic and can adversely effect the plant's aeration basin process performance and effluent quality. Return rates must be established to prevent the settled sludge from aging in the clarifier. Conversely, sludges not held long enough will not thicken properly and will be dilute and difficult to concentrate. If the return sludge pumps are operated at too high a rate, the thickening benefit of the final clarifier will be lost. The operators balance these opposing issues by varying the return sludge pumping rate.

- The operation of the waste sludge pump represents the greatest operational control that can be used to manipulate the activated sludge process. The amount of sludge wasted from the activated sludge plant ultimately acts to establish numerous other process control parameters including the microbial population, F/M ratio, MCRT, sludge age, MLSS settability, bacterial growth rate, and overall process performance. Either too little or too much sludge wasting can have a dramatic impact on the operation of the activated sludge system.

In general, the treatment plant operators must continually adjust the biological process to maintain an optimal environment for bacterial growth, to maintain an appropriate balance between the food entering the plant and the biomass held under aeration, and to produce a mixed liquor that will settle well in the final clarifiers. The ability for a plant to create a properly settling sludge can be correlated to the growth rate of the bacteria held under aeration.

As previously discussed, the growth rate of microbes in the system is related to the ratio between organic food in the incoming sewage and the bacterial population held under aeration as measured by the F/M ratio. Also, as was previously discussed, some of the organic carbon entering the aeration basin as primary effluent BOD will be biodegraded to carbon dioxide by the respiration process while the rest will be converted to new cells via the synthesis process. The operator's selection of an appropriate F/M value for the process will play a major role in deciding how much new sludge will be synthesized and how well the new sludge cells will settle in the final clarifiers.

If the operator chooses to control the plant in a manner that promotes a high F/M ratio, the bacteria will grow at a rapid rate. Much new sludge will be synthesized and the plant will have to waste sludge frequently to maintain a young sludge age and low MCRT. In essence, the operator is maintaining a small number of microbes in the MLSS relative to a large amount of BOD that is entering the reactor. When operated in this manner, the new cells that form are often dispersed and difficult to flocculate. The effluent leaving the final clarifier may look clean, but it may contain large clumps of poorly flocculated straggler or dispersed floc. This is typical of a facility operated in the high rate mode.

At the other extreme, the operator might choose to control the process in a manner that creates a low F/M ratio. Under these conditions, the bacteria will be in a starvation mode and will be digesting themselves through endogenous decay. This will reduce the amount of sludge that the plant must waste. The overall plant's sludge age will be old and the MCRT will be high. In essence, the operator is maintaining a high MLSS concentration relative to the low amount of available food entering the system as BOD. The tradeoff against the positive gain resulting from reduced sludge wasting is the negative potential for a system operating in this mode to produce a poor quality effluent. Since the microbes are in a starvation mode and digesting themselves, many individual cells will be lysed and broken open. The organic portions of the dead microbes will be consumed by other living bacteria; however, the inert or inorganic portions of the cell will tend to accumulate in the system. This leads to a rapidly settling, heavy sludge that neglects to flocculate well and leaves a lot of fine, ash particles suspended in the effluent. This condition is called pin floc. The plant's final effluent may appear to be cloudy and turbid. This condition is typical of a plant operated in the extended aeration mode.

The best settling sludge is usually attained in the conventional operating mode at moderate sludge ages, balanced F/M ratios, and moderate MCRT values. In this zone, the bacteria are healthy and have an optimal amount of food available to sustain their population. Under these conditions, the bacteria will form a well developed slime layer around their cells that helps them to flocculate and settle well. There are enough flocculated cells present to avoid dispersed floc, yet they are young enough to avoid pin floc. Plants operated in this mode are considered to be conventional plants.

From the above discussion, it would appear that all operators should strive to achieve a conventional mode of operation in order to produce the best effluent. This is not always the case. If an industry was discharging its effluent into a municipal sewer system and only wished to partially treat the wastewater to reduce its strength, it might choose to pretreat the wastes using a high rate approach. Conversely, small towns that do not have the resources to waste sludge everyday, or that wish to reduce the amount of sludge that they must process, may choose the extended aeration mode. Pin floc from the extended aeration process can be accommodated provided that the final clarifiers are oversized to capture the pin floc.

A microscopic evaluation of the aeration basin's mixed liquor will allow the operators to correlate the type of microbes observed to the settleability of the sludge. Figure 7 relates the types of microbes grown in the system to the settling quality of the MLSS. As discussed, young sludges at high F/M and low MCRT will exhibit dispersed straggler floc and an abundance of amoebas and flagellates. Old sludge with a low F/M and high MCRT will exhibit a turbid pin floc full of stalked ciliates, rotifers and nematodes. Good settling sludge at a moderate sludge age, F/M, and MCRT will have an abundance of free swimming ciliates and stalked ciliates under the microscope.

The operator causes the plant's F/M and MCRT to shift by adjusting the sludge wasting rate. This alters or maintains the amount of MLSS held under aeration and keeps the F/M and MCRT in the selected target range for the plant. If solids are not properly wasted from the system, the F/M will shift on its own and the process will seek a new equilibrium balance independent of the operator's target ranges. As shown on Figure 8, there is one pathway for organic mass to enter the aeration basin, namely as primary effluent BOD, and two paths for mass to leave the system, namely as either waste sludge solids or as effluent solids. If the operator fails to waste sufficient sludge, the plant will seek to achieve its own equilibrium by allowing solids to be wasted out the effluent pipe. Since this effluent pipe is regulated by an EPA and DEP license that allows only small solids losses, this is not the appropriate pathway by which MLSS should be wasted. The operator's best opportunity to control the plant's effluent quality is through an aggressive wasting program that keeps the upstream process in equilibrium. A process control strategy for wasting sludge is usually based upon maintaining a target MLSS level, F/M, or MCRT that has been chosen over time to provide the best quality effluent in the plant. It is important to note that all wasting approaches have a scientific basis in the biological growth kinetics that are established

Figure 7 - Microorganism Predominance Vs. Settleability

Figure 8 - WAS Mass Balance

at given F/M values. This means that a wasting approach based upon MCRT or MLSS values is still fundamentally based on F/M concepts because the F/M changes automatically if MLSS or MCRT is adjusted. Operators often prefer the F/M approach because it is direct, but use the MCRT or MLSS method become they do not have to wait five days to obtain BOD test results.

BIOLOGICAL PROCESS FAILURES

If optimal biological growth can be achieved in the treatment process, then the microbial cells will readily assimilate organic pollutants into their cells, flocculate and settle in the plant's final clarifiers, and leave clean water behind. The fact that this relatively simple process often goes awry in actual practice suggests that there are many potential factors that can adversely impact the treatment process and create less than optimal biological conditions. Many of these factors result in poor floc formation and inadequate settling in the clarifiers.

An ideal MLSS floc is shown in Figure 9. The floc consists of a group of coagulated bacterial cells held together by the adhesive character of the slime layer that surrounds each healthy cell. The cells, when considered as a whole, represent the bacterial microstructure of the floc. Holding the cells together is a fabric of filamentous organisms that constitute the floc's macrostructure. Unlike round or oval floc forming cells, the filaments consist of long, stringy organisms that form a grid between the cells. The filaments add strength to the floc and help to hold it together as it settles.

When the ideal floc leaves the aeration basin as MLSS and flows to the final clarifier, it settles in two phases. If placed in a settling vessel in the laboratory, the MLSS will initially occupy the entire vessel's volume. Soon, a well defined interface will appear between clean water at the top of the vessel and dark sludge below the interface. The interface will drop quickly at first and create a clear supernatant behind its downward movement. Later, the interface will continue to move downward more slowly as the settled sludge thickens in the bottom of the vessel. These two phases can be viewed graphically in Figure 10.

In order for successful clarification and settling to occur, the MLSS must drop to the bottom of the clarifier quickly during the rapid clarification phase. In order for successful sludge thickening to occur, the settled sludge must have the ability to compact under its own weight during a slow compaction phase. Many factors can lead to poor clarification and compaction. Some of these major problems are discussed as follows:

Figure 9- Optimal Floc Formation

Figure 10 - Activated Sludge Settling phases

SOLUBLE BOD BREAKTHROUGH

Soluble BOD breakthrough occurs when the clarified supernatant in the final clarifiers is still high in dissolved organic content as measured by the BOD test. This is an indication that some of the influent organic matter was not properly assimilated into the MLSS cells in the aeration basins. This is an early warning of major process problems because, under normal conditions, microbes should rapidly remove all soluble BOD from the water. Some potential causes for BOD breakthrough include:

- A toxic waste has entered the system and killed the MLSS population such that they are no longer available to biodegrade the wastes.
- The plant may be nutrient deficient which makes the bacteria unable to complete their biodegradation process.
- Concentrated high strength BOD loadings from the raw sewage influent stream, or from sidestream sludge dewatering or digestion processes, may be overloading the plant.
- High flows through the aeration basins may have reduced their hydraulic detention time below that which is needed to provide minimum BOD removal levels.

This problem can usually be solved by removing toxic loads, adding sufficient nutrients, controlling high strength sidestreams, or reducing excess flows in the sewer system.

PARTICULATE BOD BREAKTHROUGH

High effluent BOD may result from the excessive carryover of MLSS into the final effluent. This is usually the result of high effluent TSS levels caused by the presence of organic MLSS cells. Even though the TSS represents bacteria cells instead of raw sewage, high solid levels would still be considered a license violation by EPA and DEP. High BOD levels would result since the TSS is organic in nature and will show up in the BOD test as organic matter. If particulate BOD breakthrough occurs, it can only be solved by determining why the MLSS is not settling well in the clarifier.

DISPERSED STRAGGLER FLOC

If individual MLSS microbial cells remain individually suspended instead of properly flocculating, a poorly settling dispersed floc will occur. Clean water may be visible in the clarifier, but clumps of non-flocculated solids will also be seen washing out over the clarifier's weirs.

As discussed, dispersed floc is often caused by high F/M, low MCRT, and young sludge conditions. The aeration basin population may be too low for the amount of food being treated. This problem can be corrected by wasting less MLSS and allowing the MLSS to increase. This will eventually raise the MCRT and lower the F/M to the point that dispersed floc should no longer occur.

Other factors can lead to dispersed floc as well. High upstream BOD levels that occur in short slug bursts may cause localized high F/M levels in the aeration basins. This could occur over brief periods even though the overall daily F/M readings for the plant were in range. Upstream peak loadings should be equalized to prevent this problem from occurring.

The discharge of surfactant chemicals from commercial laundries, food processing plants, or dairy facilities may also cause settling problems in the plant. Surfactant compounds may blur the otherwise clear liquid to solids interface in the daily MLSS settling test. A poorly defined interface as the MLSS settles could be an indication of possible upstream surfactant or detergent loads.

Yeast discharges can lead to dispersed floc. If large bakeries, breweries, or food processing plants connect to the sewer system, the yeast can prevent the floc from settling properly. The source of the yeast should be identified and controlled.

PIN FLOC

As previously discussed, pin floc occurs during periods of low F/M and high MCRT. This is caused by too little sludge wasting and too many microbes being held in the plant for the available food supply. The starving microbes consume each other leaving rapidly settling cell inerts behind. These fragments settle too quickly to sweep small pin floc particles out of the water and a turbid effluent is left. This situation can be corrected by wasting more sludge to increase F/M levels and to decrease the MLSS level and MCRT.

SOLIDS FLUX LIMITATIONS

The solids flux to a clarifier, as defined by the units of lbs/day of MLSS mass per square feet of clarifier surface area, is a measure of the solids loading applied to each unit surface area of the clarifier. It is measured by the following equation:

$$\boxed{\text{SOLIDS} = \frac{(Q+Qr)(MLSS)(8.34)}{A}}$$

Where Q = plant flow in MGD
Qr= return sludge flow in MGD
MLSS= mixed liquor solids concentration in mg/l
A = clarifier surface area in square feet

The solids flux of the clarifier represents the rate at which the liquid to solids interface propagates downward during the rapid clarification mode. Every clarifier has a limiting solids flux that represents the maximum rate at which solids can be applied to the clarifier surface. If solids are applied at a flux rate greater than this rate, the solids interface will rise upward and eventually flow over the weirs.

For typical activated sludges, the maximum flux rate that can pass through a clarifier is 24 lbs/day/SF of MLSS at an SVI of 100 ml/mg. This loading may increase to 48 lbs/day/SF for brief periods of peak hourly flows. If solids loadings greater than this amount are added, the clarifier will fail. This suggests that an operator may wish to lower the plant's MLSS concentration or return sludge rate anytime that the plant flow is high or that a clarifier is out of service. By not exceeding the limiting solids flux of a clarifier system, rapid downstream settling of the sludge blanket is more likely to occur.

The allowable solids flux, or loading, onto a clarifier's surface is a function of the amount of filaments present in the mixed liquor as indicated by the plant's sludge volume index (SVI). Table 12 relates the maximum allowable solids loading flux on the clarifiers to the SVI of the plant.

TABLE 12:

RELATIONSHIP OF APPLIED CLARIFIER SOLIDS FLUX TO SLUDGE SETTLEABILITY AND FILAMENT POPULATION

SVI (mg/l)	AVG. DAILY FLUX (LBS/DY/SF)	PEAK HOURLY FLUX (LBS/DAY/SF)
75	30	60
100	24	48
125	23	46
150	20	40
175	18	36
200	15	30

RISING SLUDGE

Rising sludge occurs in a clarifier when the MLSS at first settles to the bottom of the reactor, but then rises back to the surface. This occurs when sludge is held for too long in the clarifier and becomes septic. As oxygen is depleted, bacteria in the sludge begin using nitrate for biodegradation and then release nitrogen gas. This tends to float the sludge blanket to the surface and may lead to effluent quality or scum problems. This problem can be minimized by maintaining maximum sludge blankets of one to three feet in the clarifier and by turning the clarifier's contents over every hour.

FILAMENTOUS SLUDGE BULKING

As discussed, filaments typically remain in the MLSS background and form a macrostructure framework upon which good settling floc is built. Under certain conditions, the plant may experience a filament bloom where filaments take over the system. This usually occurs when specific environmental conditions occur that favor filaments over less hardy floc-formers. As shown in Figure 11, excessive filaments hold the floc-formers apart and keep them from flocculating or compacting. This may lead to very clean water around the filaments, but significant MLSS washout to the receiving water will occur due to the poor MLSS settling. When filaments take over a treatment system, it is said to be undergoing "bulking". Many conditions in the treatment plant can lead to bulking. These include the following:

Figure 11 – sludge bulking

- Low or high pH
- Low dissolved oxygen
- Low nutrient levels
- High sulfur content
- Septic wastes and volatile acids
- High or low F/M levels

In all cases, filaments take hold when an adverse environmental condition makes it hard for the floc formers to survive. Filaments are able to decompose wastes under conditions that are not acceptable for the floc-formers. Unfortunately, the filaments do not settle well and often are lost in the plant's effluent. The sludge volume index (SVI) test provides an early warning of potential filamentous bulking problems. The SVI is calculated as follows and is a measure of how much volume a unit weight of MLSS will occupy:

$$\text{SVI}=\frac{\text{(30MINUTE SETTLING TEST)(1000)}}{\text{MLSS IN MG/L}}$$

Upon calculating the SVI value on a given day, it can be compared against the standard values listed below in Table 13:

TABLE 13:

SVI VALUES AS BULKING INDICATION

SVI VALUE	INTERPRETATION
100 or less	Rapid settling
100	Good settling
150	Incipient bulking
150 or more	Bulking occurring

If the SVI test reveals high values and sludge bulking conditions, a microscopic evaluation of the MLSS should be conducted to identify the filament type. Several filaments may be present, but it is important to determine which filaments are present in predominance. The most predominant filament is an indication of current conditions in the system. Less prevalent background filaments are indications of past process problems that may have since been resolved. The reactor conditions or environments that promote the predominant filament type should be identified and evaluated. Several factors that can lead to filament blooms include the following:

- Low dissolved oxygen levels in the aeration basins or clarifiers can lead to outbreaks of Type 1701, S. natans, and H. hydrossis filaments. The low dissolved oxygen can result from insufficient aeration, poorly designed aeration equipment, improper aeration basin mixing, shock loadings of septic wastes, excessive MLSS solids levels, and high F/M levels in the reactor.

- Nutrient deficiencies in the system can cause outbreaks of Type 021N, Thiothrix, Type 0041, or Type 0675 filaments. Low nutrient levels can occur if excessive industrial wastes are present, if high levels of food processing or carbohydrate wastes are discharged, or if high pH conditions cause the available nutrients to become chemically unavailable for microbial metabolism.

- Low pH levels in the system can lead to outbreaks of Nocardia. The source of the low system pH could include background water levels, septic conditions in the reactor, excessive sludge ages, nitrification, or upstream waste loads containing acid compounds.

- Sulfides present in the treatment plant can lead to outbreaks of Thiothrix, Type 021N, Beggiatoa, or Type 0914 filaments. The source of the sulfides may be upstream industrial discharges, septic conditions in the sewer system, poor aeration or mixing in the aeration basins, excessive sludge ages, or low pH conditions.

- High soluble BOD loadings from food processing plants containing large sugar or starch components can lead to S. natans, Type 021N, Thiothrix, H. hydrossis, N. limicola, or Type 1851 filaments.

- Complete mix aeration plants with high MCRT and low F/M can cause Thiothrix, S. natans, Type 1701 and M. parvicella filaments to form.

- High MCRT and long sludge ages can lead to outbreaks of Nocardia, M. parvicella, Type 0092, Type 1891, and Type 0675 filaments.

FILAMENTOUS FOAMING

Filamentous foaming is caused by Nocardia, M. parvicella, and Type 1863 filaments. It is manifested by thick, brown, sticky foam all over the aeration basin's surface. These types of filaments are hydrophobic and prefer to attach to air bubbles at the reactor's surface than the bulk liquid in the tank. Nocardia is one of nature's most hardy microbes. It can biodegrade almost any waste material including oil and grease. The foam can become so thick that it can entrap all of the MLSS from the aeration basin and draw it up to the surface layer. The thick foam can also become septic and odorous.

The primary causes of Nocardia foaming are excessive oil and grease in the influent, excessive MCRT and sludge ages, too low F/M levels, anaerobic sludge digestor return streams, low pH, and nitrification. Once established, Nocardia is very difficult to eliminate. MCRT levels should be reduced, especially in the summer when temperatures over 18°C favor Nocardia. In addition, scum, oil and grease should be wasted from the plant's surfaces. Nocardia foam should be removed from the system and wasted since this is where most of the active organisms will be found.

EFFLUENT DISINFECTION

Raw sewage is high in waterborne disease carrying organisms called pathogens. While a reduction in pathogens will occur as raw sewage passes through each biological treatment unit process, residual pathogen levels in the plant's treated effluent will generally still exceed safe levels for human health. Following the treatment process, clean water from the plant's final clarifiers must be disinfected prior to its discharge to the receiving water.

Disinfection with liquid sodium hypochlorite bleach is common. When added to the effluent, the sodium hypochlorite creates a residual of hypochlorous acid as follows:

$$NaOCl \leftrightarrows Na^+ + OCl^-$$

$$H^+ + OCl^- \rightleftarrows HOCl$$

Both HOCl and OCl^- constitute the free chlorine residual in the plant's effluent and both have disinfection properties; however, HOCI is eighty times more effective in killing pathogens than OCl^- . As shown in Table 14, the extent at which the sodium hypochlorite dissociates into either compound is a function of pH.

TABLE 14:

DISSOCIATION OF SODIUM HYPOCHLORITE IN WASTEWATER

pH	% HOCI	% OCl
6.0	97	3
9.0	3	97

The data in Table 14 shows the importance of monitoring the effluent pH when establishing chlorine dosages for disinfection. If the plant's effluent pH rises from 6.0 to 9.0, most of the residual will exist as OCl^-. This will require a sodium hypochlorite dose of eighty times that which is needed at a pH of 6.0 when most of the residual exists as HOCl. In order to optimize chlorine disinfection rates, the plant's effluent pH should be maintained as close to neutral as possible.

All of the chlorine applied to a plant's effluent will not be converted to an available residual for disinfection. Before a residual can be established, the chlorine demand of the effluent must be satisfied. Chlorine demand is defined as the amount of applied chlorine that is consumed by the effluent before any measurable residual is obtained. Several concurrent chemical reactions with chlorine remove it from the effluent before it can be used for disinfection. These components of chlorine demand include:

- Some of the applied chlorine dose is consumed by chemical reactions with inorganic ions in the water.

- Some of the applied chlorine dose is consumed by chemical reactions with organic materials in the water. These materials include any remaining TSS or BOD that is being lost in the plant's effluent. Should a treatment plant be producing a dirty effluent with a large carryover of pollutants, it will be more difficult to disinfect the effluent due to its chlorine demand. In addition, pathogens may be harbored within some of the solids floc being carried into the effluent and thus escape full disinfection.

- Some of the applied chlorine will react with ammonia in the water to form chloramine compounds through the following reactions. These compounds are referred to as combined residual and have some minor wastewater disinfection properties:

$$\begin{array}{l} NH_3 + H^+ \rightleftarrows NH_4^+ \\ HOCl + NH_4^+ \rightleftarrows NH_2Cl \\ HOCl + NH_2Cl \rightleftarrows NHCl_2 \\ HOCI + NHCl_2 \rightleftarrows Ncl_3 \end{array}$$

- Some of the applied chlorine dose reacts with the newly formed combined chlorine residual and further degrades into chloramine compounds.

All of the above elements of chlorine demand must first be satisfied before the applied chlorine dose results in a free residual for disinfection. Typically, an applied chlorine dose of 2 to 10 mg/l is needed to achieve appropriate disinfection levels in properly treated activated sludge effluent.

In addition to the chlorine residual, the effectiveness of chlorine disinfection is also impacted by the available reaction time. Generally, thirty minutes of detention time at average flows and fifteen minutes at peak flows is required. Chlorine reactors are usually designed to create these detention times under plug flow hydraulic conditions in long serpentine channels with at least a 40/1 ratio of length to width. This ensures that all of the wastewater volume will be exposed to the applied chlorine dose and held for a uniform detention time without short-circuiting.

Sodium hypochlorite solutions degenerate over time and lose their disinfection strength. The rate of degeneration is increased by light and heat. As the hypochlorite solution ages, especially in the summer, it may be necessary to add more solution to obtain the same degree of pathogen reduction.

Wastewater discharge licenses often contain a maximum upper chlorine residual limit that may be discharged to the receiving water in the plant's final effluent. This is due to concerns regarding the long term effects of chlorine toxicity in the environment. Chemicals containing sulfite ions are often added to the effluent to remove the chlorine residual as follows:

$$\begin{array}{l} SO_3^{-2} + HOCl \rightarrow SO_4^{-2} + H^+ + Cl^- \\ SO_3^{-2} + NH_2Cl + H_20 \rightarrow SO_4^{-2} + NH_4 + Cl^- \end{array}$$

The ratio of free chlorine dissolution by the addition of sulfite compounds is about 1:1; that is, 1.0 mg/l of residual will generally be removed by 1.0 mg/l of sulfite solution. Sodium biosulfite is commonly used to provide the sulfite ions needed for dechlorination. The reaction rate for dechlorination is instantaneous and only a short detention time is required. Usually, dechlorination can be achieved in only two minutes at average daily flow rates and two seconds at peak hourly flow rates.

SLUDGE PROCESSING

As discussed, excess sludges must periodically be removed from the primary clarifiers and the activated sludge process to keep the plant's F/M, MCRT, and MLSS levels at an optimal equilibrium. When wasting sludge, only the solids content or mass of microbes wasted has an impact on the process. Unfortunately, this waste mass is often contained in large volumes of water. Even the thickest waste activated sludge is seldom more concentrated than a 1% solution. This means that 99% of the waste sludge volume is water. As a result, the plant operators must remove, convey, and transport large volumes of water in order to remove small volumes of actual sludge mass. This is often problematic in treatment plants with poorly conceived sludge handling systems. Many treatment plants perform poorly because operators choose not to waste as much sludge as they should because of the costs and nuisance conditions associated with its removal.

Wastes sludges also have a high volatile solids or organic content. This means that they will continue to biodegrade once removed from the plant. This can lead to odor generation issues and the creation of nuisance conditions. It is important to properly operate plant processes that help to reduce the organic content of the waste sludge. A sound sludge management strategy should include the consideration of both water volume reduction methods and organic content reduction approaches.

The reduction of excess water in the primary raw sludge begins in the primary clarifier. As the TSS in the raw sewage influent is settled in the clarifier, a sludge blanket is formed at the reactor’s bottom. The weight of the blanket forces the solids to compact and excess free water is squeezed out of the pore spaces between the solids particles. In general, raw primary sludge will typically concentrate to 1 to 3% solids in the clarifier. Industrial paper mill sludges may concentrate to thicker levels.

The reduction of excess water in the waste sludge begins right in the plant’s final clarifier. Generally, the return sludge pump can be manipulated to create thickened sludge at the bottom of the clarifier that is two to three times as thick as the MLSS concentration that entered the clarifier from the aeration basin. This is critical because doubling the solids concentration of the sludge is equivalent to halving its water volume.

If possible, the waste sludge should be held in a thickening system and allowed to further settle and decant. The addition of polymers may help improve the decanting and solids thickening process. Polymers help to neutralize the electrical surface charges that exist on individual sludge particles. These charges are of like polarity and tend to hold the solids particles apart. Polymers act to remove these charges and cause the particle suspension to collapse thereby allowing water and solids to separate.

Primary sludges are often thickened in gravity thickener reactors which are essentially small clarifiers that resettle the sludge that was drawn from the clarifier. The act of resettling the previously settled primary sludge often allows additional water to separate from the solids. It is not unusual to develop a thickened primary sludge concentration of 3 to 5 percent in a gravity thickener.

Waste activated sludge is more difficult to thicken by gravity since its specific density is nearly identical to that of water. The cell mass contained in the waste sludge is often more conducive to floating than to settling. For this reason, waste sludge is sometimes thickened by flotation on dissolved air flotation (DAF) units instated of in gravity thickeners. A DAF unit promotes flotation by adding air bubbles below the incoming waste sludge solids. This allows the solids to float to the surface and concentrate to 1 to 3 percent solids. The thickened waste sludge is then scraped off the DAF surface and further processed.

The organic and water contents of a waste sludge can be further reduced in an aerobic digestion process. In this system, waste sludge is held under aeration for long periods of time without any external source of organic food. This causes microbes in the sludge to digest themselves via the following biodegradation reaction:

$$\text{Microbes} + \text{oxygen} \rightarrow \underset{\text{dioxide}}{\text{carbon}} + \underset{\text{compounds}}{\text{inert}}$$

After a prolonged aeration period, nearly all of the biodegradable portion of the sludge organics will be converted to carbon dioxide. The remaining sludge will be either inert inorganic ash or non-biodegradable refractory organic materials. There is a two-fold benefit to waste sludge digestion as follows:

- The oxidization of organic matter in the sludge to carbon dioxide will result in the reduction of a significant portion of the sludge volume.

- As MLSS cells are digested, their walls will be lysed and broken open. This will result in the release and removal of additional intercellular water that was formerly held inside the sludge cells.

Finally, a sludge dewatering process is often used to further reduce the volume of the sludge by removing excess water. Drying beds, belt presses, and centrifuges are often used to dewater sludges.

The benefit of sludge thickening and digestion can be seen in Table 15 for an example where an operator wishes to waste 1500 lbs/day of MLSS sludge mass over a one year period which is at an MLSS concentration of 2500 mg/l (0.25%). Assuming that the sludge is 80% volatile, the data in Table 15 shows that the final disposal volume can be reduced by over 99% over the course of a year using sludge thickening and digestion, and dewatering:

TABLE 15

ANNUAL BENEFITS OF WASTE SLUDGE THICKENING, DIGESTION AND DEWATERING

SLUDGE PROCESS	TOTAL MASS (LBS)	VOLATILE BIODEGRADABLE MASS (LBS)	% SOLIDS	DISPOSAL VOLUME (GAL)
Aeration basin	550,000	440,000	0.25%	26,000,000
Final clarifier	550,000	440,000	0.75%	9,000,000
Thickening system	550,000	440,000	1.00%	6,500,000
Aerobic digestor	330,000	0	2.00%	2,000,000
Belt filter press	330,000	0	18%	200,000

The data in Table 15 shows that the 26,000,000 gallons of MLSS wasted per year can be reduced to a final volume of only 200,000 gallons if proper thickening, digestion and dewatering is achieved. This occurs as the result of the removal of water from the sludge by thickening and digestion and the reduction of the sludge's volatile organic solids portion through digestion.