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THE PROCESS CONTROLLER's GUIDE TO

THE MICRO-BIOLOGY OF WASTEWATER TREATMENT

This is number 11 in the Process Controller Guide series of documents

Number 1	Pollution Control.
Number 2	Water Sources and Water Treatment**.**
Number 3	Wastewater Treatment
Number 4	Phosphorus Removal from Wastewater.
Number 5	Electricity and Electric Motors.
Number 6	Pumps, Blowers and their Operation.
Number 7	Mechanical Transmission of Power.
Number 8	Flow Measurement
Number 9	Iron and Sulphur compounds in the water and wastewater environment.
Number 10	Management, Supervision and Related Matters.
Number 11	**The Microbiology of Wastewater Treatment.**

This guide is not intended to be a detailed and comprehensive manual on the microbiology of wastewater treatment.

It is intended that this document be a useful reference and training manual guide to all persons involved in the Water and Wastewater Industry.

This Process Controller Guide is dedicated to the memory of Tony Bowers who did so much for all Process Controllers in the life critical profession of Water and Wastewater Treatment.

NOTE:
Credits: some information was obtained via Google. Where original authors/owners could be determined, this is indicated.

THE PROCESS CONTROLLER's GUIDE TO

THE MICROBIOLOGY OF WASTEWATER TREATMENT

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THE PROCESS CONTROLLER's GUIDE TO

THE MICROBIOLOGY OF WASTEWATER TREATMENT

PART 1.

WHAT IS A CHEMICAL PROCESS?

1.1 INTRODUCTION.

In a chemical process, there is a change in the composition or chemical make up for the material or materials. This can generally take place in one of two ways:

1. direct reaction of two reactive chemicals: for example chlorine reacting with ammonia

$$Cl_2 + H_2O + NH_3 \rightarrow NH_4Cl + HOCl$$

2. indirect where there are a number of chemical reactions in which the various steps are performed by micro-organisms. This will be referred to as bio-chemical processes.

In water treatment, most of the reactions are direct reactions even though there may be a number of steps. The various reactions of aluminium sulphate when used as a coagulant, is an example of this.

In wastewater treatment, in contrast, there are few direct reactions as the bulk of the treatment process is performed by micro-organisms. This Process Controller's Guide will look at the various organisms that perform the wastewater treatment processes and on how the Process Controller can optimise the treatment processes.

This guide will concentrate mainly on the Activated Sludge treatment process as this is where the Process Controller has the biggest influence on the effectiveness of the treatment process. The Process Controller running a Bio-filtration treatment works has relatively few options to effect process changes.

1.2 THE ROLE OF MICRO-ORGANISMS IN THE WASTEWATER TREATMENT PROCESS.

Wastewater from various sources differs widely in quality and quantity. The Process Controller plays a major role in ensuring the wastewater treatment processes are operated to their highest efficiency and effectiveness.

A wastewater treatment works is a microbiological zoo that houses bacteria, protozoa, metazoa and other micro-organisms. These microorganisms do the actual breakdown and removal of nutrients and organic material in the wastewater. They perform at their best when all their basic requirements such as food, oxygen etc. are met.

Wastewater treatment works are designed to allow the natural process of the breakdown of pollution to occur under controlled conditions. These systems include physical and chemical processes to remove solids and heavier materials. However, left behind is the liquid containing soluble and insoluble organic material. The one process all wastewater treatment works facilities have in common is the biological treatment of this organic material or "nutrients".

That is, they rely on the use of certain microorganisms to convert these organic nutrients into two separate streams – a high quality effluent and a sludge stream. Wastewater contains nutrients of every type: phosphorus, nitrogen, sodium, potassium, iron, calcium and compounds such as fats, sugars and proteins. Microorganisms use these substances as a "food" source for energy, for the synthesis of cell components and to maintain life processes.

The role of the Process Controller is to maintain the right conditions in the treatment system for the right type of microorganisms. If the right conditions are not present, the wrong microorganisms will dominate. These “wrong” microorganisms not only interfere with the successful removal of wastes from the water, but they themselves may be difficult to remove from the system.

Many types of microorganisms can be found in the wastewater treatment system. However, the types of organisms that will dominate will be the ones that are best suited to the “environment” or conditions in the system Virtually all of the micro-organisms that provide the necessary treatment are too small to be seen by the human eye. – this is why they are called micro-organisms

Bacteria are usually about 0.001 mm in size. Protozoa are somewhat bigger, but generally not visible to the human eye. To see these organisms, one requires a microscope.

Unfortunately, there are extremely few Process Controllers that have access to a microscope or to a laboratory that could provide a microbiological examination of a particular sludge. This means that the Process Controller has no idea of the types and relative abundance of the various micro-organisms in the treatment process. This means that the Process Controller is totally reliant on physical examination of the sludge and on certain chemical parameters to assess the efficiency and effectiveness of the treatment process.

The physical examination would include the following:

1. how well does the sludge settle;

2. is there good floc formation;

3. how clear is the effluent from the secondary sedimentation tank.

The chemical parameters would include the following:

1. the Chemical Oxygen Demand of the treated effluent and the overall removal;

2. the Ammonia content of the treated effluent and the overall removal;

3. the Suspended Solids content of the treated effluent and the overall removal.

Activated sludge is a mixture of micro-organisms that come in contact with and digest biodegradable materials (food) from wastewater. Once most of the material is removed from the wastewater, microorganisms form floc and settle out as sludge. Some type of micro-organism will always grow in the system. The organisms that will dominate will be the ones that are best suited to the environment. So, it is important that the Process Controller create an environment that will foster the type of micro-organisms that is preferred — floc-forming bacteria. It will be seen later that some filamentous organisms should be present to help produce a well settling sludge and a clear effluent. If there are too many filamentous organisms then the sludge will not settle well and will not compact well.

THE PROCESS CONTROLLER's GUIDE TO

THE MICROBIOLOGY OF WASTEWATER TREATMENT

PART 2.

THE VARIOUS MICRO-ORGANISMS FOUND IN A WASTEWATER TREATMENT WORKS.

2.1 INTRODUCTION.

There are three main types of micro-organisms found in a wastewater treatment works. These are; including their relative predominance:

1. Bacteria - 95%;
2. Protozoa – 4%;
3. Metazoa – 1%

2.2 CLASSIFICATION OF BACTERIA.

Bacteria are single-celled microorganisms that come in three basic shapes:

1. bacillus, which is rod- shaped, square or rectangular;
2. coccus, which is round or oval shaped;
3. spirillum, which is spiral or cork-screw shaped.

The parts of a typical bacterium is shown below in figure 1 below.

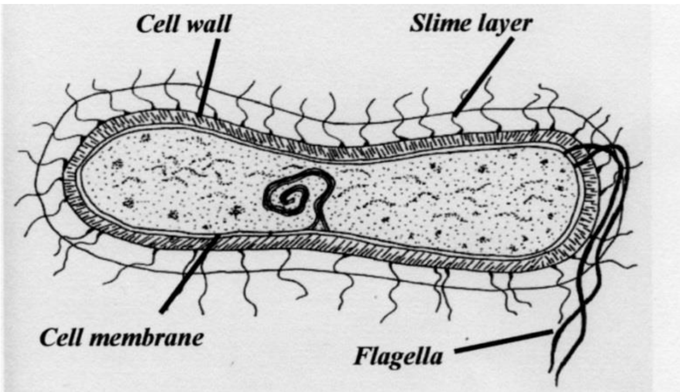


Figure 1: SHOWING THE PARTS OF A BACTERIUM.

Bacteria may be classified based on how they respond to oxygen:

1. Aerobic bacteria require oxygen to live;
2. Facultative bacteria prefer oxygen but can survive for some time without it. Some can utilise the oxygen in nitrates (NO_3) as an oxygen source. This was covered in section 7.6 in PC Guide 3;

3. Anaerobic bacteria that cannot live in the presence of oxygen. These were covered in detail in PC guide no. 3 under Anaerobic Digestion.

The most important microorganisms in the activated sludge system are the aerobic bacteria. They consume the biodegradable material found in wastewater. They consume proteins, carbohydrates, fats and many other compounds.

It is very important to note that bacteria can only consume **soluble** organic material. Solid particles of "food" must be eaten by a two-step process.:

1. Adsorption;

2. Absorption.

During a**d**sorption, food particles that are too big to pass through the cell membrane and bacteria stick to each other. The bacteria secrete enzymes, which dissolve food particles into very small units. These small units of food can now pass through the bacteria's cell wall.

A**b**sorption is the process by which smaller dissolved units of food pass into the cell membrane.

2.3 THE ROLE OF ENZYMES.

As noted above, most of the micro-organisms are bacteria and that bacteria can only consume soluble organic material. In the influent wastewater, a lot of the organic material is not soluble and therefore initially unavailable to the bacteria. This is where compounds known as enzymes play a critical role.

Enzymes are compounds that are made by living organisms for the purpose of helping biochemical reactions to occur. All biochemical reactions require enzymes. Bacteria need the enzymes to breakdown nutrients into a soluble form. The names of enzymes usually ends in "ase". For example, example that break down proteins are called ***proteases*** and those that breakdown fats (also called lipids) are called ***lipases***.

Enzymes are strange compounds that only work when the conditions are right. If the enzymes do not work, the bacteria will not function properly and will not survive.

2.4 GROWTH CHARACTERISTICS OF BACTERIA.

In a typical activated sludge system after preliminary and sometimes primary treatment, the influent enters the reactor - also known by other names such as aeration tank. To ensure good contact with the organisms that will undertake the treatment process, organisms are returned from the underflow of the secondary sedimentation tank. This is usually known as return sludge. The mixture of influent wastewater and the return sludge in the reactor is called "mixed liquor".

When the influent wastewater first enters the aeration basin it contains a high level of nutrients or food. Here at the head end of the basin there is plenty of food available and bacteria use the food mostly for growth and some for energy.

In the past, the reactor often contained only one compartment and the layout was known as a completely mixed reactor. The idea was to "spread" the load throughout the reactor and so reduce the aeration requirements at the inlet end of the reactor. This layout is very rarely used these days as this layout does not allow for anoxic and anaerobic zones that are required for nutrient removal. This aspect is covered in greater detail in PC guides 3 and 4.

A growing bacterium has flagella (hair-like structures on the outside of the cell). The flagella make it able to move in search of food. They are multiplying rapidly and do not settle to form floc. When food is limited however, most of the available food is used for energy and cell maintenance. There is less food left for growth, thus less reproduction occurs. The bacterium takes steps to conserve energy by losing its flagella. The waste products start to form a thick slime layer outside the cell wall causing the bacteria to stick together to form floc.

The detention time must be sufficient in the aeration basin to allow an area to develop where the amount of food is low. If the microorganisms are in the basin for too short a time, they will still be actively swimming and multiplying and will not form floc. This will yield a turbid effluent. This is another reason why the completely mixed reactor is generally no longer used these days. A simplified illustration of the decrease in "food" concentration with the increase in detention time is shown in figure 2 below:

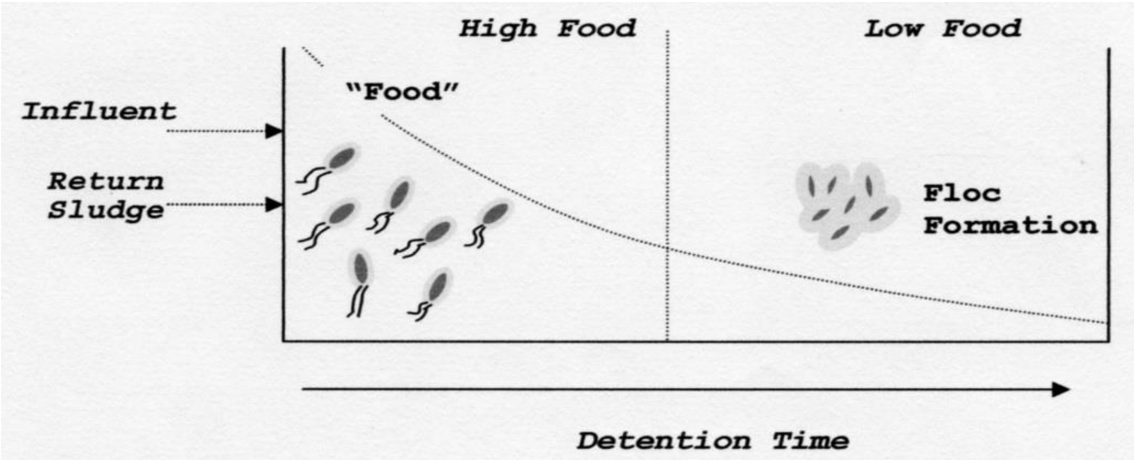


Figure 2: SHOWING THE DECREASE IN FOOD CONCENTRATION WITH DETENTION TIME.

2.5 THE BACTERIA GROWTH CURVE.

The various organisms go through a number of growth phases during their lives as listed below:

1. Lag-phase.

   During the lag-phase, bacteria are becoming acclimated to their new environment. They are digesting food and are developing the enzymes need to break down the types of nutrients that the bacteria have detected. Growth does not occur during this phase;

2. Exponential Growth-phase

   Bacteria begin to grow at a rapid rate because of the excess amount of food that is available. The cells are mostly dispersed and active. They are not sticking together to form floc. Towards the end of this phase reproduction slows down because there is no long an excess amount of food. There are a large number of bacteria that have to compete for the remaining food. The bacteria begin to lose their flagella;

3. Stationary-phase.

   Because of the lack of food, some bacteria are reproducing but an equal number are also dying. So, the number of bacteria remains relatively constant. They have not lost all their flagella and have formed a stick substance covering the outside of the cell wall which allows them to agglomerate into floc;

4. Death-phase.

   In this phase the death rate increased with little or no growth occurring. The total number of bacteria keeps reducing. Bacteria in the activated sludge system must be allowed to hang out in the aeration basin until they reach the stationary-phase. If they flow out of the basin too early, they will be active and motile and will not settle out as floc.

These phases are shown in figure 3 below:

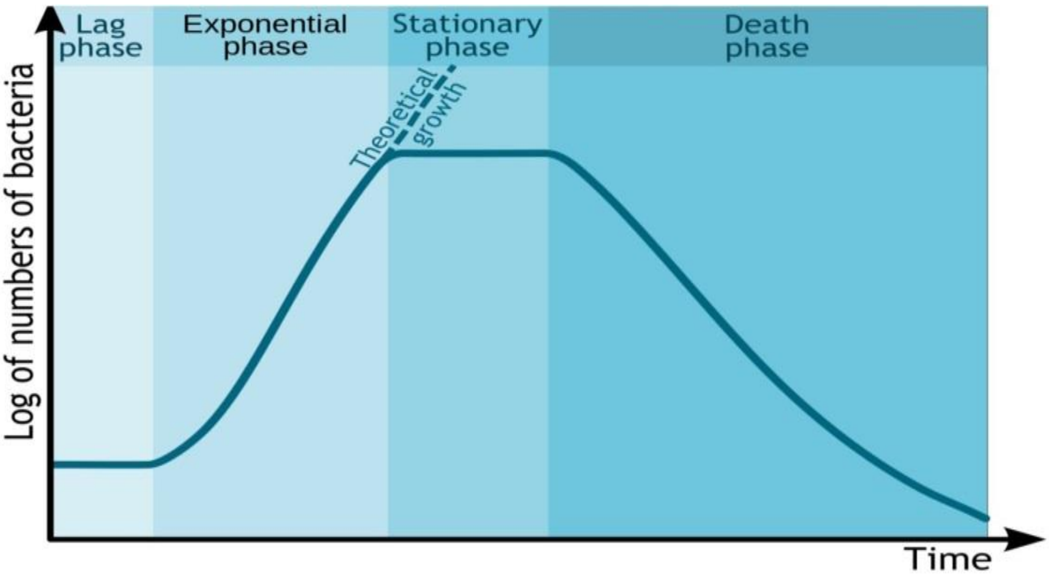


Figure 3: SHOWING THE VARIOUS GROWTH PHASES.

2.6 THE ROLE OF PROTOZOA IN THE WASTEWATER TREATMENT PROCESS.

While 95% of the microorganisms in activated sludge are bacteria, only 4% are Protozoa. Protozoa contribute very little to the removal of organic nutrients however their presence greatly enhances the clarity of the treated wastewater. While bacteria are difficult to see under the microscope, Protozoa are not. The behaviour and the numbers of the different types of protozoa will give an indication of treatment system health and performance.

Protozoa are single-celled microorganisms that come in a large variety of sizes and shapes. Their main function in the treatment process is to remove non-flocculent bacteria and very small floc that would not settle. They can be classified based on the way they “eat”. Holozoic protozoa are capable of ingesting food such as bacteria through special mouths. Holophytic protozoa absorb dissolved nutrients directly into their cells just like bacteria.

In the activated sludge process, they may be classified into five categories:

1. Amoeba;
2. Flagellates;
3. Free-swimming ciliates;
4. Crawling ciliates;
5. Stalked ciliates.

2.7 THE ROLE OF AMOEBA AND FLAGGELATES IN THE WASTEWATER TREATMENT PROCESS.

Amoebae are the most primitive single celled protozoa. They feed mostly on solid particles in the water and will slowly extend lobe-like projections called pseudopodia until it has completely surrounded its food. After the food is surrounded, it secrets enzymes that will break the food particle into smaller units that will be absorbed into the cell. There are two types of amoeba; the naked amoebae and the testate amoebae. The naked amoeba is the one most are accustomed to seeing in the science book. It looks like a blob. The testate amoebae has a shell or “test”. Some secrete substances to form the shell while others form a shell from debris it collects as it travels in the water.

Amoebae can only multiply when the nutrient level in the aeration basin is quite high or if there is very little competition for the food. Therefore they can only dominate early in the process. If large numbers of amoeba are found in a sample collected from the discharge end of the aeration basin (where most of the nutrients should be removed), this may indicate one of the following:

1. A shock load of organic material in the influent wastewater. This would make extra food available that will allow them to compete.

2. The presence of large amounts of particulate matter. Amoeba favour particulates.

3. Lack of oxygen. Amoebae move very slowly and require less oxygen then other protozoa.

Most flagellates absorb nutrients just like bacteria so they compete with bacteria for dissolved nutrients. Flagellates peak in number while the soluble food concentration is high and the number of bacteria is still quite low. This, just like with amoeba is usually early in the process. However, once the bacteria become acclimated to the environment, they multiply much faster than flagellates and will eventually out compete them for soluble nutrients.

An example of an amoeba is shown in figure 4 below:

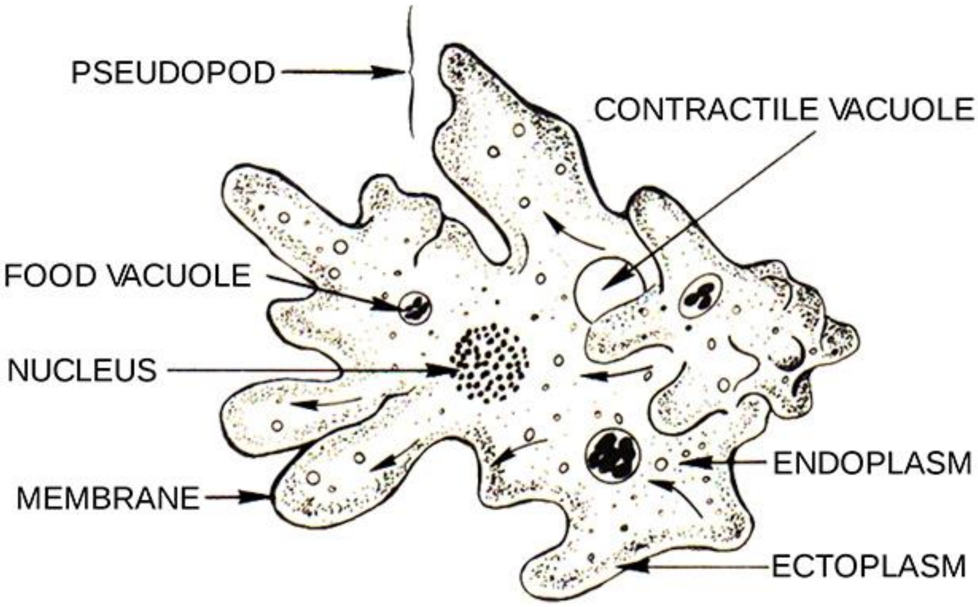


Figure 4: AN EXAMPLE OF AN AMOEBA

2.8. THE ROLE OF CILIATES IN THE WASTEWATER TREATMENT PROCESS.

Ciliates also contribute very little to the removal of organic material from the wastewater. They feed on bacteria, not on dissolved organics. Bacteria and flagellates compete for dissolved nutrients but ciliates compete with other ciliates and rotifers for bacteria. The presence of ciliates is usually an indication of good treatment. They dominate after the formation of floe and when most of the organic nutrients have been removed. They are necessary for removing excess bacteria and algae from the fluid and clari1'ing the effluent.

Ciliates can be classified into three categories.

1. Free-swimming ciliates;

2. Crawling (grazing) ciliates;

3. Stalked (sessile) ciliates

2.8.1 Free-swimming Ciliates.

Free-swimming ciliates swim freely in the fluid. They are usually covered with “cilia” which are hair-like projection that they used for locomotion and for sweeping food into their mouths. They appear as the flagellates begin to disappear. As the bacteria population increases much of the organic nutrients have been removed and there is a lot of disperse bacteria available for feeding. Free-swimming ciliates begin to dominate as they feed on the increased number of bacteria. A typical free swimming ciliate is shown in figure 5 below:

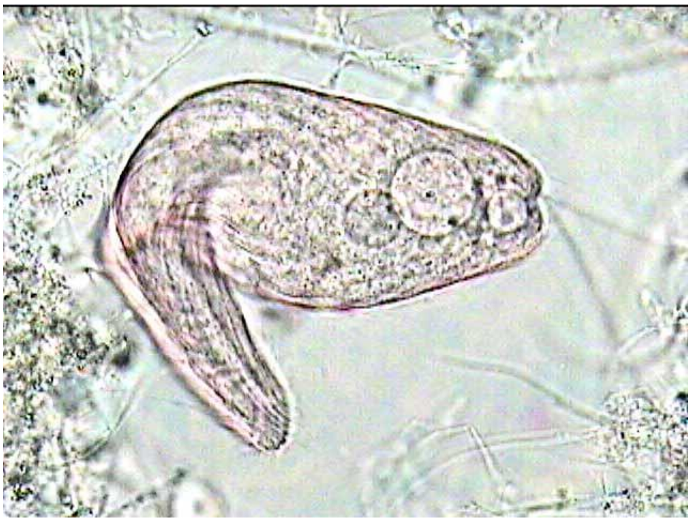


Figure 5: AN EXAMPLE OF A FREE SWIMMING CILIATE.

2.8.2 Crawling Ciliates.

As the amount of nutrients decrease, food is limited and the bacteria begin to lose the flagella and form a sticky slime layer that allows them to stick together to form floe. As floc particles enlarge, crawling ciliates begin to dominate. Crawling ciliates have cilia on the underside of the body. The cilia are twisted together to form “tufts” or legs that are used for crawling along the floc. Crawling ciliates graze on floc particles and feed on the straggling bacteria on the edges of the floe. As the population of disperse bacteria decreases and floe increases crawling ciliates out compete free-swimming ciliates because they can find food within the floe and the free-swimming ciliates cannot. Some examples are shown in figure 6 below:

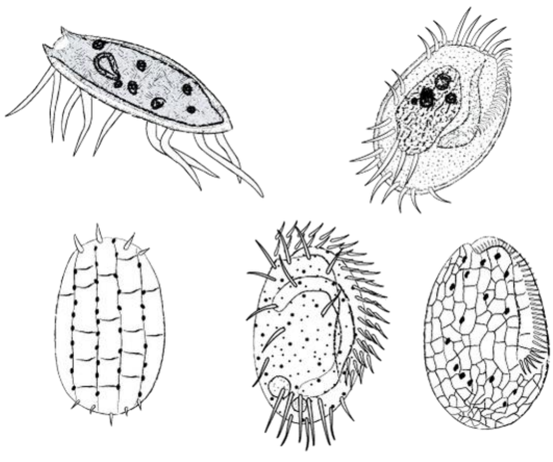


Figure 6: SHOWING SOME EXAMPLES OF CRAWLING CILIATES.

2.8.3 Stalked Ciliates.

Stalked ciliates only have cilia surrounding the oral groove or mouth and are used to create a current that will bring food into the mouth. Stalked ciliates appear in mature sludge. They dominate when most of the dissolved nutrients have been removed. In Mature sludge, crawling ciliates and stalked ciliates compete for dominance. While crawling ciliates must crawl around to find food, stalked ciliate can anchor themselves on the stalk and bring the food to them.

Stalked ciliates grow singly or in colonies. Single stalked ciliates have one “zooid” or head per stalk. Colonial stalked ciliates can have up to 300 heads branching from one or more stalks. As the sludge ages and less and less food becomes available, the colonial stalked ciliates begin out compete the single stalked ciliates for dominance. in simple terms “the more head on the stalk, the older the sludge.”

As the sludge continues to age other types of stalked ciliates begin to compete for dominance. Stentors are large bell shaped protozoa that also uses cilia to sweep food into the mouth but while others can only hold enough food to fill the mouth, the Stentor can fill its entire body with food.

Vorticella have a bell shaped body on a long stalk. The Acineta will wait for an unsuspecting protozoan and will suck it into its tentacles, secrete a toxin to paralyze it and will begin to suck the body juices out. Some examples of stalked ciliates are shown in figure 7 below:

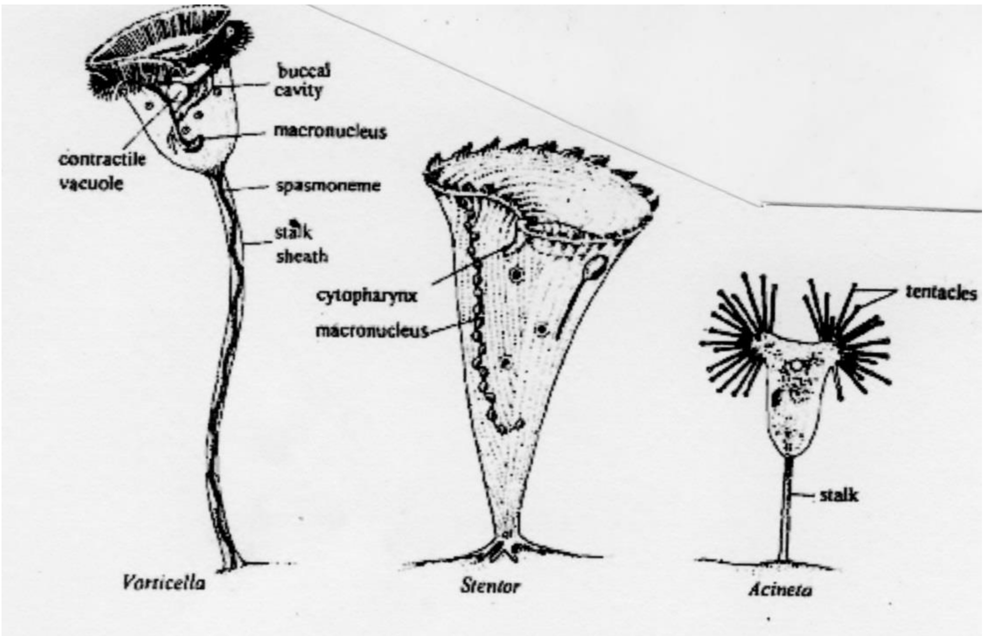


Figure 7: SHOWING SOME EXAMPLES OF STALKED CILIATES.

2.9 THE ROLE OF METAZOA IN THE WASTEWATER TREATMENT PROCESS.

Metazoa are multi-cellular microorganisms that feed on bacteria, algae and protozoa. They can vary from having very simple to highly complicated physical structure. The various types of metazoa are commonly found in the wastewater treatment system are:

1. Rotifers;
2. Nematodes;
3. Tartigrades (water bear);
4. Annelids;

5. Ostracods (Daphnia);

6. Copepods (water flies and mites).

2.9.1 Rotifers.

Rotifers are commonly found in wastewater treatment systems and play a principle role in the activated sludge treatment but they should never be dominant in the system. They do an excellent job of polishing off and removing any remaining material in the water. They also secrete a sticky substance that helps the floc to remain firm and clumped together. Rotifers come in a variety of sizes and shapes and as male and female.

Most rotifers in the treatment system are female since the male's only purpose for existence is to fertilize the female and die. Rotifers are good indicators of wastewater toxicity. They are usually the first to be impacted by a toxic load.

Examples of some rotifers are shown in figure 8 below:

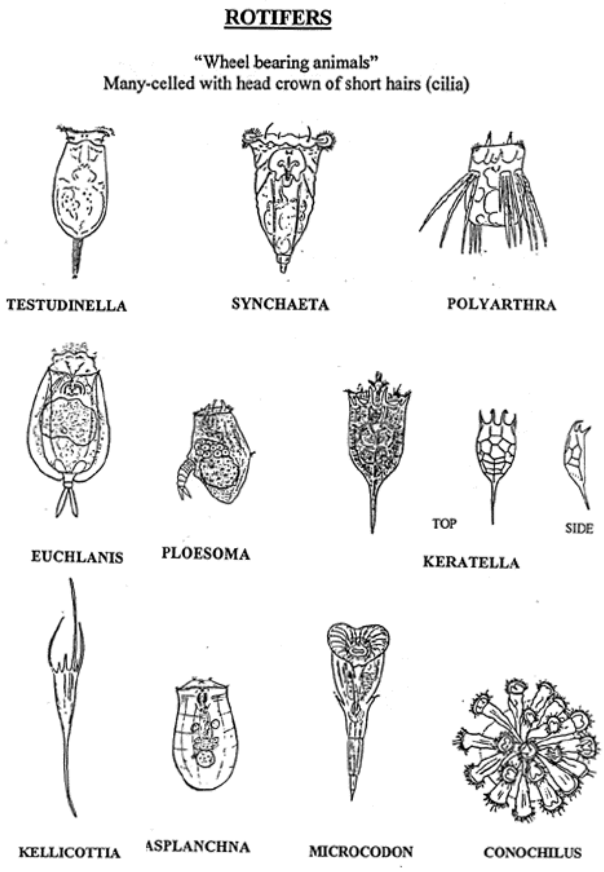


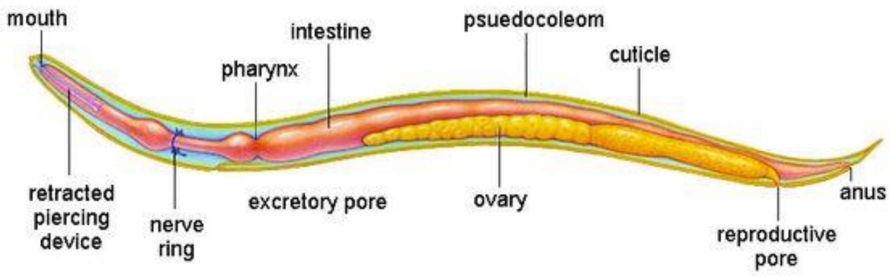
Figure 8: SHOWING SOME TYPES OF ROTIFERS.

2.9.2 Nematodes.

Nematodes may be seen in significant amounts in longer aged systems or older sludges. They do not contribute to the overall treatment and feed on bacteria, protozoa, fungus and sometimes they eat other nematodes. Some nematodes have teeth and some have a spear they can stick into their prey and then use the spear to suck in food like a straw.

Some nematodes are able to grow in the human body and will finish up the influent wastewater. THe most common are the Roundworm (Ascaris Lumbricoides); Whipworm (Trichuris Trichuria) and Hookworm (Ancylostoma Duodenale). In the body, they cause stomach and intestinal cramps and a general lowering of one's health, making one more prone to the effect of other diseases.

An example of the body construction of a nematode is shown in figure 9 below:



water.mecc.edu

Figure 9: SHOWING THE BODY CONSTRUCTION OF A NEMATODE.

2.9.3 <u>Tartigrade (Water Bear).</u>

Water bears are commonly found in the same environment with rotifers and nematodes. They feed on algae and small protozoa. The interesting thing about them is they have developed ways to survive extreme environmental swings. If there is not enough oxygen, they swell up like a balloon and float around for a few days. When the environment dries up, they shrivel up like raisin. They are however, very sensitive to toxic conditions. Their presence usually indicates that there is little to no ammonia present

Water bears have five body segments and four pairs of short stumpy legs with claws and can be seen in different colours; red, orange or even green. They have a head with eyes and a mouth that they use to pierce their food before sucking out the inner parts. The body construction of a water bear is shown in figure 10 below:

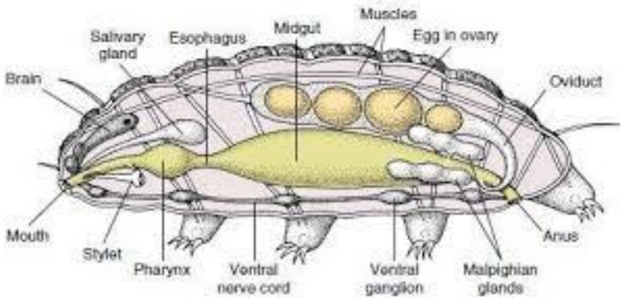


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Figure 10: SHOWING THE BODY CONSTRUCTION OF A WATER BEAR.

2.9.4 <u>Annelids.</u>

Free-swimming annelids occur occasionally in wastewater treatment works and feed on the sludge. Sometimes red worms are seen in maturation ponds. An example of a red worm is shown in figure 11 below:

teamaquafix.com

Figure 11: SHOWING AN EXAMPLE OF A RED WORM.

2.9.5 Ostracods (Daphnia).

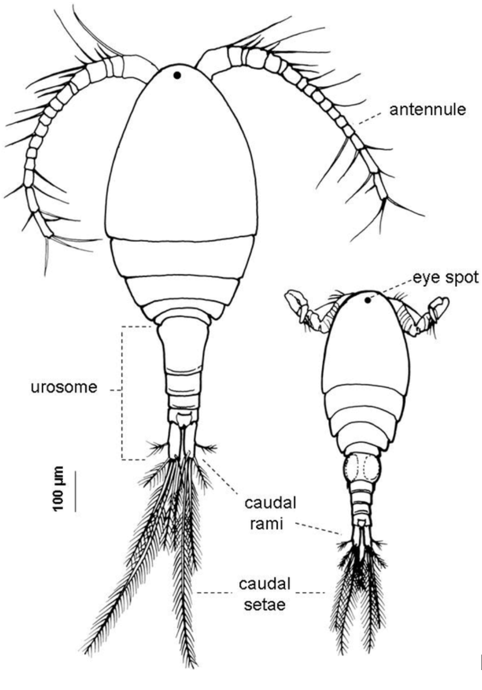
These are only found in high quality effluents in maturation ponds. They are a good source of food for fish. An example of a Daphnia Magna is shown in figure 12 below:

sciencephoto.com

Figure 12: SHOWING A DAPNIA MAGNA.

2.9.6 Copepods (water flies and mites).

These are also only found in high quality effluents in maturation ponds. They are a good source of food for fish. An example of a Copepod is shown in figure13 below:



bioone.org

Figure 13: AN EXAMPLE OF A COPEPOD

2.10 THE FOOD CHAIN.

The wastewater treatment process forms part of a food chain. The bacteria start off the treatment process and are in turn consumed by protozoa. The protozoa in turn provide food for the metazoa. In the aquatic environment, the metazoa are a food source for fish. The fish can be a food source for humans. As one progresses up the food chain, the quality of the environment necessary for the survival of each species becomes higher. For example: in the reactor, a dissolved oxygen content of 2 mg/l is sufficient and the Ammonia content can exceed 30 mg/litre. For fish to survive in water, the dissolved oxygen content should be at least 5 mg/litre and the Ammonia content should be less than 1 mg/litre.

2.11 FACTORS AFFECTING BACTERIA GROWTH.

It is the role of the Process Controller to provide the best possible environment for the floc-forming bacteria to grow. The Process Controller can control some of the conditions they require and there are some conditions that they cannot control. For instance, the Process Controller has no control of the weather and very little control over the types and amount of nutrients entering the treatment plant. So, it is important that the Process Controllers understand how the following factors affect the growth of the bacteria.

1. Oxygen Utilization;
2. Sludge Age;
3. Dissolved Oxygen;
4. Mixing;
5. pH value;
6. Temperature;
7. Nutrients.

2.11.1 Oxygen Utilization.

Actively growing bacteria eat food at a rapid rate therefore using oxygen at a rapid rate. The rate of oxygen use is normally termed the Oxygen Uptake Rate and is measured in mg O/hr/g of MLSS. Generally a higher Uptake Rate is associated with a higher F:M ratio and younger sludge ages. A lower Uptake Rate is associated with a lower F:M ratio and older sludge ages.

2.11.2 Sludge Age.

As bacteria first begin to develop in the system they grow singularly, in small clumps and chains. They are very active with flagella and do not have a well-developed slime layer. The bacteria are dispersed and do not settle well. As the sludge is allowed to age, bacteria lose their flagella and accumulate more slime. The small clumps and chains begin to stick together and form floc large enough to settle.

2.11.3 Dissolved Oxygen.

Aerobic bacteria require at least 0.1 - 0.3 mg/L of oxygen to survive. At least 2 mg/L of oxygen must be maintained in the bulk fluid in order for the bacteria in the centre of the floc to get 0.1- 0.3 mg/L of oxygen. If not, the bacteria in the centre will die and the floc will begin to break up.

2.11.4 Mixing.

Mixing is required to bring the bacteria, oxygen and nutrients in contact with each other. Once the food is limited, the bacteria lose their flagella and can no longer swim. Without sufficient mixing, the bacteria will not bump into each other to form floc and proper treatment will not take place

2.11.5 pH value.

It is the bacterial enzymes that are very pH dependent. Their optimal pH is between 6.5 and 7.5. Rapid pH changes should be avoided.

The writer recalls an incident where a company accidently discharged 5 tons of sulphuric acid down the sewer. All industries in this treatment works catchment area had previously been asked to report any such major discharge to the treatment works Manager. In this case, it took 12 hours for the acid to reach the treatment works. This gave the staff time to obtain bags of lime to neutralise the acid and to increase all internal recycled flow to the maximum possible. With sufficient warning, the effect on the treatment works was minimal and within a few days, the effluent returned to its usual high quality.

2.11.6 Temperature.

Biochemical reactions are temperature dependent. Reactions are slower in colder temperatures so the system will require more organisms to do the work. Reactions are faster in warmer temperatures therefore fewer bacteria are required to do the same job during the summer months.

2.11.7 Nutrients.

Bacteria require basic nutrients for growth (carbon, nitrogen, phosphorus) as well as trace amounts of sodium, potassium, magnesium and iron. All these are present in normal domestic wastewater. Generally, industrial wastes do not contain sufficient nutrients and must be supplemented. This will be covered in more detail later.

2.12 FACTORS AFFECTING PROTOZOA GROWTH.

Like bacteria, there are several factors that influence how the protozoa will grow in the .treatment system.

1. Temperature;
2. pH;
3. Dissolved Oxygen;
4. Nutrients.

2.12.1 Temperature.

Most protozoa can survive and reproduce in the temperature range of most activated sludge systems. However, they grow best in ambient temperatures of 15 - 25 degrees C.

2.12.2 pH.

Protozoa are more sensitive to pH than floc-forming bacteria are. They have an optimum range of 7.2 - 7.4 but can tolerate 6.0 - 6.8.

2.12.3 Dissolved Oxygen.

Like bacteria, protozoa must have oxygen to survive. A low dissolved oxygen content will severely limit the kind and number of protozoa present.

2.12.4 Nutrients.

Most municipal wastewater systems contain sufficient nutrients to support most protozoa. Industrial wastes are more likely to be deficient in nutrients.

2.13 FOOD: MICRO-ORGANISM RATIO

The food to microorganism (F:M) ratio measures the amount of food that is available for the amount of microorganisms present in the aeration basin. The amount of food is determined by the biochemical oxygen demand (BOD) or chemical oxygen demand (COD) test. If there is too much food and not enough microorganism (high F:M ratio), settling problems may occur because in the presence of excess food bacteria are active and multiplying and will not develop into floc.

$$\frac{F \quad \text{(Determined by the BOD or COD test)}}{M \quad \text{(Determined by the MLVSS)}}$$

On the other hand a low F:M ratio indicates that there is a little bit of food and a lot of microorganisms. This means that food is limited, the bacteria lose their flagella. They are no longer multiplying but are forming the slime layer needed to develop floc. However, one must be careful not to operate with a F:M ratio that is too low. When food is severely limited, nutrient deficient conditions may occur which can cause other problems – see later.

Process Controllers will be familiar with the term "Sludge Age" of an activated sludge works. The relationship between Food: Micro-organism ratio and the Sludge age will become clearer later in this guide.

As the amount of food in the system reduces, the types and numbers of the various micro-organisms will change. This will be dealt with in greater detail in Part 3.

THE PROCESS CONTROLLER's GUIDE TO

THE MICROBIOLOGY OF WASTEWATER TREATMENT

PART 3.

UNDERSTANDING THE ACTIVATED SLUDGE PROCESS.

3.1 INTRODUCTION.

It would help Process Controller understand the activated sludge process better if they could see how the various aspects of the process are interrelated. Possibly the best way of demonstrating the interrelation of the various factors in the activated sludge process is using the "Relative Predominance Diagram". This diagram illustrates the information necessary to successfully operate an activated sludge system. Figure 22 (on the next page) is a Relative Predominance Diagram for an activated sludge system.

In the real world situation, food is entering the treatment works all the time. This makes it difficult to understand exactly how the types and number of the various micro-organisms changes with time.

To explain the process more easily, a batch reactor under ideal conditions is used. Ideal conditions may be described as a temperature of 20ºC, pH between 6.5 and 8.5, dissolved oxygen concentration of at least 2 mg/L, sufficient nutrients, and no toxic substances. Here there is a "once off" discharge of wastewater (food) into the reactor.

Here one starts at time zero with the wastewater being introduced into the reactor and is aerated. Samples are removed at intervals and their contents studied. What is found is detailed below.

In Figure 22, proceeding from left to right, the horizontal axis represents aeration time. This can also be related to increasing sludge age. The vertical axis represents the **relative** number of organisms.

This axis is not to true scale as the number of organisms varies greatly. The number of bacteria is many times as great as the number of rotifers. If the diagram were to true scale it would be very hard to work with as micro-organisms other than bacteria would form a very small portion at the bottom of the chart.. The main purpose of this diagram is to indicate at what stage in the activated sludge process the various organisms reach their peak number.

The **dashed** line in Figure 22 represents the food remaining. The top of the graph at the left axis represents the total initial food added or initial Chemical oxygen demand (COD) of the wastewater. As the process proceeds to the right, the food or COD drops to a very low level at the right side of the graph. The **dotted line** on Figure 22 represents the mass of organisms existing at any given time. Initially in the batch system the total number of organisms is very low. As the process proceeds, the total mass increases rapidly until it reaches the maximum mass of organisms which the remaining amount of food can support.

At that time, the mass of organisms begins to decrease as some of the organisms enter into a predominantly endogenous phase and begin to die. At any point on the horizontal axis or the time line, we have a given amount of food or COO and also a given mass of microorganisms. If we divide the amount of food remaining by the mass of microorganisms we will have the F: M (food-to-micro-organism) ratio for that given point and also the common distribution of microorganisms for that food-to-micro-organism ratio. As we proceed to the right, the food decreases and up to a point the microorganisms increase, as the food-to-micro-organism ratio decreases and the sludge age increases , .

HERE ONE CAN SEE THE INVERSE RELATIONSHIP BETWEEN F:M RATIO AND SLUDGE AGE.

One says "inverse" because as the F:M ratio gets SMALLER; the sludge age gets BIGGER.

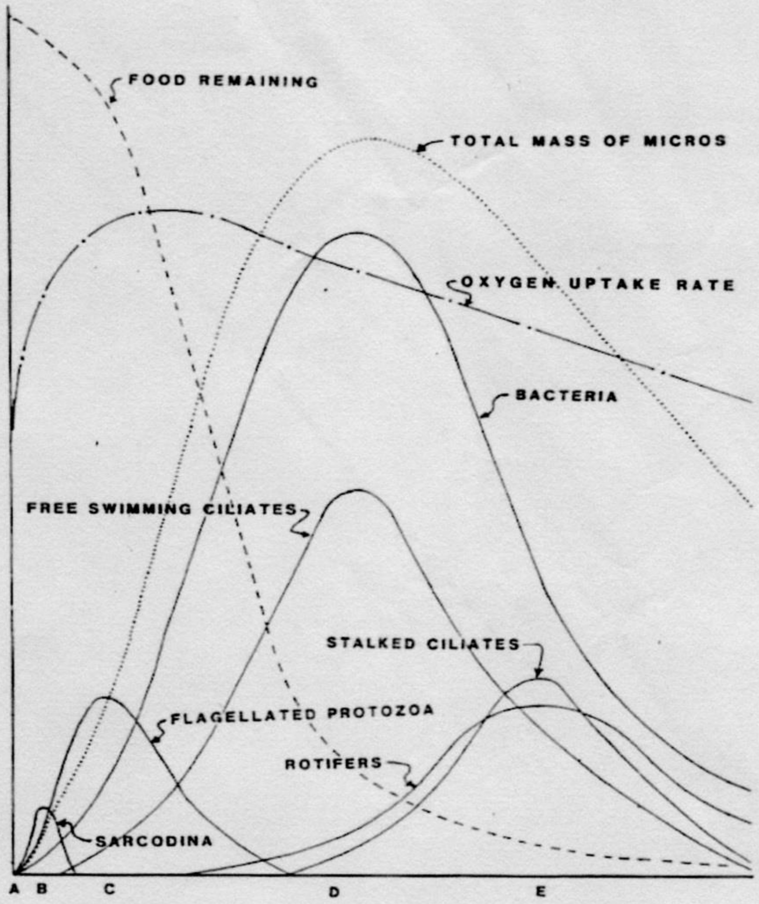


Figure 1.

The Relative Predominance Diagram

Key Points

A *The process begins as fresh wastewater is introduced into the tank and aeration starts. Microorganisms are present, but none dominates.*

B *Sarcodina, a primitive organism, reaches its peak. This organism can only exist in significant numbers when the food supply is high.*

C *Flagellated protozoa reach maximum numbers. These organisms are much more active than sarcodina, and use up the food supply at a high rate.*

D *Free swimming ciliates and bacteria reach their greatest numbers. Both are able to survive with a lower food supply than flagellated protozoa. This is the area where the conventional activated sludge mode operates.*

E *Stalked ciliates and rotifers predominate. There is no longer enough food to support the mass of microorganisms. Cells die off; the rotifers and stalked ciliates can consume bacteria.*

Figure 14: THE RELATIVE PREDOMINANCE DIAGRAM.

The **dash and dotted** line in Figure 14 represents the oxygen uptake rate (OUR) of the process. As there are few microorganisms at the beginning of the process, the OUR is low but increases rapidly as the number of microorganisms increases. The OUR is not only related to the mass of the microorganisms but also the activity of the cells. For this reason, it is always better to express the oxygen uptake rate as **mg oxygen per hour per 1 000 mg MLSS**. The oxygen uptake rate reaches a maximum slightly before the total mass of cells reaches a maximum then slowly begins to decrease.

3.2 BEGINNING THE PROCESS.

3.2.1 Point "A".

This represents the beginning of the batch treatment process. At this point, one begins with a tank of domestic wastewater under the ideal conditions described above. The fresh wastewater has been introduced into the tank and the aeration has just begun.

Microorganisms necessary for complete activated sludge treatment are present in normal domestic wastewater. At point "A" no organism has a significant predominance. Throughout the process many types of organisms are present, but under ideal conditions most of these organisms do not reach populations great enough to have a significant effect on the process. Later one will see that if ideal conditions are not maintained some undesirable organisms can reach significant numbers and influence the process.

3.2.2 Point "B".

This represents the point in time when the sarcodina organisms reach their peak numbers. The sarcodina, are very primitive organisms. The amoeba is the most common sarcodina organism. The sarcodina move slowly and are rather inefficient in competing for food. They can only exist in significant numbers when the food supply is high. This point has little significance in the study of the activated sludge process. The only time this condition would occur in an actual activated sludge process is being started up for the first time or is recovering from complete toxicity after all the microorganisms have been killed.

3.2.3 Point "C".

This may be called a "Young sludge". This is the point when the flagellated protozoa reach their maximum numbers. The flagellated protozoa, have a more complex structure than the sarcodina and are much more active. This mobility allows the flagellated protozoa to obtain food when the supply is too low to support a high population of sarcodina. The high level of the flagellated protozoa increases the food requirement. When the flagellated protozoa are at their peak, the food supply is being used at a very high rate. This is the first point of major significance in the study of activated sludge.

This point is characteristic of a young sludge and the area in which the **high rate activated sludge mode operates**. Examining the batch reactor at this point, one would probably note a considerable amount of white or light brown foam. The sludge itself would be light brown in colour. Withdrawing sample and performing the 30 minute settling test, one would note a rather slow settling sludge with a cloudy supernatant. The reason for the slow settling and cloudy supernatant is the active nature of the flagellated protozoa.

This young sludge can be compared to a room of young children who are always on the move and hard to get to settle down. This high activity level by the flagellated protozoa results in a high oxygen uptake rate. The microorganisms, like humans, require more oxygen when they are very active. The COD that is removed from the wastewater is utilized for two purposes by the microorganisms (1) to create new cells and (2) to supply energy for activity. The flagellated protozoa multiply rapidly and are very active. COD removal is rapid at this point. The flagellated protozoa do not flocculate well and settle, but remain in the supernatant, giving it a cloudy appearance.

Calculation of the sludge volume index (SVI) of this sludge might show a higher than normal value because of the poor settling characteristics. A microscopic examination of this sludge would reveal a large number of flagellated protozoa and also a significant population of bacteria, with the possibility of a few sarcodina. Effluent from the process would be high in COD and moderately high in suspended solids because of the active flagellated protozoa, ciliates and bacteria.

3.2.4 Point "D".

This is a very important location on the relative predominance diagram. At this location both the free swimming ciliates and bacteria reach their greatest numbers. **This is the area where the conventional activated sludge mode operates**. Although the bacteria have a simple cell structure, they are rather efficient in competing for food as the supply is lowered. The bacteria remove food from the wastewater by two methods:

1. The first is **absorption**. In this process, the dissolved COD or food is absorbed directly through the cell wall;

2. The second - and preferred - method is **adsorption**. Bacteria have a sticky slime layer which traps or adsorbs fine suspended particles. The bacteria cannot utilize the fine suspended particles directly, but they secrete enzymes which break down or dissolve the particles so the material can be absorbed into the cell.

Bacteria are also somewhat less active than the flagellated protozoa. They require less food and have a lower OUR than the flagellated protozoa. The free swimming ciliates, have a more complex structure than the flagellated protozoa and are able to survive with a lower food supply than the flagellated protozoa. Motion of the free swimming ciliates is by activation of hair-like cilia on the outside of the cell. Like bacteria, the free swimming ciliates are less motile than the flagellated protozoa and therefore use less oxygen and utilize the reduced food supply more efficiently.

Examination of the batch reactor at this point would reveal a moderate amount of brown foam. Performing the 30 minute settling test would reveal considerable flocculation and a good settling sludge with clear supernatant. The reduced activity of the microorganisms results in a more rapid settling rate. The sticky slime layer, which the bacteria have, also allows the microorganisms to stick together forming larger floc particles that settle rapidly. A calculation of the SVI would result in a low number, indicating good settling characteristics.

Measurement of the oxygen uptake rate would show the rate beginning to drop off. This drop is caused by a decrease in the rate of conversion of food to cell matter and the lower activity level of the free swimming ciliates and bacteria compared to the flagellated protozoa. Microscopic examination of the sludge would reveal a well flocculating sludge with large numbers of free swimming ciliates and bacteria. A few rotifers, stalked ciliates and a few flagellated protozoa may also be present. Effluent from the process would be clear with low COD.

3.2.5 Point "E".

This is the point where the stalked ciliates and rotifers reach their greatest numbers. **This is a point in the extended aeration mode**. At point "E", the batch system is in the endogenous respiration phase. In this endogenous respiration phase there is no longer enough food to support the mass of microorganisms present. During this phase the microorganisms utilize stored food supplies to support life. They also reduce their activity level and the conversion of food to cell matter. Some cells die from lack of food. After death, the cells lyse or break open releasing solid cell structures that cannot be used as food by the microorganisms – this is often seen as a fine material floating on the surface. The liquid portion of the cell that can be used as food to support some of the remaining micro-organisms. Rotifers and stalked ciliates are able to consume whole bacteria in order to sustain their life processes. Examination of the reactor at this point would reveal a dark brown foam, possibly with a greasy appearance.

Performing the 30 minute settling test would show a rapidly settling sludge that flocculates poorly and has a granular appearance. The large size and lower activity level of the rotifers and stalked ciliates causes the rapid settling. The reduced bacteria population causes less flocculation giving the granular appearance. One would also probably notice some small particles floating to the surface made up of clumps of dead cell material. Calculation of the SVI would yield a very low number, indicating a dense sludge. Measurement of the oxygen uptake rate would indicate a significantly lower rate because of the sharply reduced conversion of food to cell matter and the lower activity level of stalked ciliates and rotifers. A microscopic examination of the sludge would indicate large numbers of stalked ciliates and rotifers; considerable numbers of free swimming ciliates and bacteria would also be present. Supernatant from the process at this point would be low in COD but might have a significant suspended solids level. The suspended solids level results from the clumps of dead cell matter and the reduced ability of the lower bacteria population to trap fine suspended solids.

3.3 THE REAL WORLD SITUATION.

In order to simplify, the explanation of the interaction of the various micro-organisms, the earlier section dealt with a batch system operating under ideal conditions. In the real world, there are very few treatment systems that operate under ideal conditions.

A Sequencing Batch Reactor (SBR) is a batch system in operation. This is where the wastewater enters the reactor that already contains activated sludge. It is then aerated for a number of hours. Then the aeration is turned off, the sludge is allowed to settle and the clear liquid layer is drawn off. Wastewater is again discharged into the reactor and the process is repeated. This means that the various organisms are already present when the treatment process begins.

While this is a batch process as far as the flow of wastewater in concerned; it is more like a continuous flow wastewater treatment works when considering the micro-organisms present in the reactor.

Most all activated sludges operate on the continuous flow system, where flow is always entering and leaving the system. For the present time, one still assumes that there are ideal conditions of temperature, pH, oxygen, nutrients, and no toxic substances.

There are various operating modes (layouts) while looking at the various operating modes. In order to look at the various modes we will assume we have a plug flow system where the wastewater enters one end of a long tank and proceeds along that tank as a unit until it reaches the effluent. In Process Controllers guide 3, part 7 various layouts/ operating modes are considered. The sections below link the operating mode with the types and relative numbers of micro-organisms associated with each operating mode.

3.3.1 The Conventional Activated Sludge Operating Mode.

This is the most common mode of operation and may be preceded by primary sedimentation. The F:M ratio will lie in the range of 0.15 to 0.20 and corresponds to a sludge age (Solids Retention Time – SRT) of 10 to 20 days.

The conventional activated sludge mode operates around area “D” in Figure 14. This is the area where free swimming ciliates and bacteria reach their peak. In the continuous flow system, after the flow reaches the end of the aeration tank, it enters a settling tank where the micro-organisms are allowed to settle to the bottom of the tank, separating them from the clear supernatant, which is discharged. Most of the micro-organisms are returned to the beginning of the process to be mixed with the incoming wastewater. The strength of the incoming wastewater represents the food. The total mass of micro-organisms in the system represents the micros.

One question that may arise at this time is: why not construct a very short plug flow tank, settle out the micro-organisms, and return them immediately to the beginning of the process? The micro-organisms need some time to consume and assimilate or digest the food they receive when mixed with the raw wastewater. This situation can be compared to a child passing through a sweet factory. The child will take as much of the sweets as they can, eating some of the sweets and sticking part of the rest in their pockets to eat later. If the child returns immediately to the sweet factory they will not be able to get as many sweets the second time because they will not be as hungry and also will still have some sweets in their pockets. However, if some time passes between the first and second time through the sweet factory so all the sweet have been eaten, they will be able to consume as much the second time. Likewise, if the micro-organisms are returned to the head of the process too soon, they will not be able to consume as much food. If they are given enough time to assimilate the food, they will be able to consume as much food the second time through.

3.3.2 High Rate Activated Sludge Operating Mode.

This mode operates at a low micro-organism mass resulting in a high food-to-micro ratio (Short sludge age) around point C in figure 22. The high rate mode operates in the area where flagellated protozoa reach their maximum numbers.

3.3.3 Extended Aeration Operating Mode.

The third principal operational mode is the extended aeration mode. This mode operates with a high micro-organism mass giving a low food-to-micro ratio (Long sludge age). This mode operates around area "E" on Figure 14 in an area where stalked ciliates and rotifers reach their peak numbers. Effluent from the extended aeration mode is usually low in COD, but can be rather high in suspended solids as a result of the dead cell matter.

3.4 MODIFICATIONS TO FLOW PATTERNS

The operating modes discussed above are the three principal operating modes for an activated sludge system operating generally on a plug flow regime. There are process modifications involving flow patterns that can be applied to these modes. These process modifications are usually applied to the conventional operation mode, but could theoretically be applied to any of the operating modes.

3.4.1 Completely Mixed Modification.

In this modification, the entire contents of the activated sludge tank are uniformly mixed. Theoretically the oxygen uptake rate and the microorganism population are the same at any point in the complete mixed activated sludge tank. In effect, the complete mixed modification operates at on single point on the relative predominance diagram. One advantage of this modification is any toxic substances present are spread uniformly throughout the tank and are less likely to result in a major kill of microorganisms.

If there is only one reactor that has been built and in operated as a completely mixed unit, then it is unlikely that there will be any reasonable amount of denitrification. The writer had such a single completely mixed reactor in his section. In this case, the reactor was 4.7 metres deep which is much deeper than is usual. Quite a high degree of denitrification was achieved. The dissolved oxygen content was measured at several points and at several depths and it was found that a large area in the lower part of the reactor had zero dissolved oxygen content. There was good mixing in the reactor so this informal anoxic zone worked very well. Another possible contributor to the relatively high degree of denitrification, was the strong wastewater being received. This was often over 1 500 mg/L COD and was due to a large contribution from the emptying of bucket toilets prior to sewers being installed in a part of the catchment area.

It would be possible to construct anoxic and anaerobic zones upstream of the reactor to achieve good denitrification and even biological phosphorus removal.

3.4.2 Step Aeration.

Although traditional called Step Aeration, this is in reality a Step Feed modification. In this modification, the aeration basin is similar to the plug flow basin but the wastewater is fed at several points along the basin. Only a portion of the food is fed at the beginning of the process. The process proceeds along the relative predominance diagram as in a plug flow basin, reducing the food supply as it moves along the diagram. When more food is added, the process shifts backward on the diagram to a lower sludge age or higher food-to-micro-organism ratio, then proceeds forward again on the diagram as the food is utilized. The process continues this forward and backward motion for several steps.

This modification is no longer used these days.

3.5 THE ROLE OF THE SECONDARY SEDIMENTATION TANK.

One needs to look at how the return rate and wasting rate affect the process. At high flows, the mass of micro-organisms entering the secondary sedimentation tank is higher than during periods of low flow. It would be too complicated to try to adjust the return sludge flow rate to match the rate at which the micro-organisms are entering the secondary sedimentation tank. The secondary sedimentation tank can provide enough storage to meet the short-term variations in food-to-micro-organism ratio.

As the quantity of micro-organisms in the system is continuously increasing; it is necessary to remove some of the micro-organisms on a regular basis. This is usually daily or even continuously. This is the only way a constant food-to-micro-organism ratio can be maintained.

The conventional activated sludge operational mode produces a well settling sludge, which results in an effluent low in COD and usually very low in suspended solids. This operational mode is stable and has considerable latitude in food-to-micro-organism ratios (0.15 to 0.20). The permits the use of a constant return rate can be maintained, as the food increases of decreases, and still achieve excellent results. This is usually equal to the average dry weather flow (ADWF). The excellent effluent and stability are among the reasons that this is the most popular operational mode.

3.6 THE EFFECT OF ENVIRONMENTAL PARAMETERS.

In the discussion above, reference was made to “Ideal Conditions”. In the real world, these are unlikely. It is, therefore, useful to look at certain environmental parameters to see the effect on the treatment process. Up to this point, it has been assumed that there are ideal operating conditions for the activated sludge system. The sections below indicate the effect on the system when the conditions are not ideal.

3.6.1 The Effect of Temperature.

If the temperature is lower than the ideal of 20º C, the entire reaction will be slowed, the Relative Predominance Diagram will be stretched out, and each peak on the curve will occur at a greater sludge age. To obtain the same COD removal, the sludge age must be increased or the food-to-micro-organism ratio must be decreased. The general reduction in the reaction rate of the micro-organisms also reduces the oxygen uptake rate. The colder water in the settling tank is more dense, resulting in slightly slower settling sludge. Increasing the sludge age to obtain a more rapidly settling sludge may offset the reduction in the sludge settling rate.

On the other hand, a higher than ideal temperature tends to increase the reaction rate and increase the oxygen uptake rate. Both of these increases could result in a reduced dissolved oxygen content, especially at the feed end of te reactor. Under high temperature conditions, the Relative Predominance Diagram will be shortened and the various micro-organisms will reach their peak at a lower sludge age.

In chemistry, as a Rule-of-Thumb, an increase in temperature of 10º Celsius doubles the reaction rate. This is not necessary true for micro-organisms as most micro-organisms have a temperature range which they prefer. Moving outside this range would result in a lower growth rate.

3.6.2 The Effect of pH value.

In general, the main organisms involved in wastewater treatment prefer the pH value to be in the range 6.5 to 7.5. In this range, optimum treatment will take place.

If the pH drops below 6.5, filamentous bacteria will be able to compete with the desirable micro-organisms and increase greatly in numbers. Nitrification bacteria are adversely affected as the pH value drops.

At a pH between 5.0 and 6.5 fungi are able to compete with the bacteria. When they increase significantly in numbers, they cause bulking of the sludge.

At a pH of 4.0 to 5.0, the fungi will predominate over the bacteria and any bacteria present will tend to be of the filamentous variety causing serious sludge bulking.

Above a pH of 8.5 to 9.0, a severe retardation of the process occurs resulting in an effect similar to the effect on the micro-organism population from reduced temperature.

3.6.3 The Effect of Dissolved Oxygen Content.

At least 2 mg/L of oxygen must be maintained in the bulk fluid in order for the bacteria in the centre of the floc to get 0.1- 0.3 mg/L of oxygen. If not, the bacteria in the centre will die and the floc will begin to break up. When the DO level falls below 0.5 mg/L, The filamentous bacteria can survive at lower DO levels and is often the reason for a poor settling sludge – this will be covered in more detail later..

Dissolved oxygen levels above 2.0 tend to waste power and the increased turbulence can shear the floc, retarding settling.

3.6.4 The Effect of Nutrient Imbalance.

If the required nutrients are not present, the fungi and filamentous bacteria will again tend to predominate, causing sludge bulking. This occurs when influent wastewater is deficient in nitrogen or phosphorus. Bacteria generally require 10 mg/L of nitrogen and I mg/L of phosphorus for every 100 mg/L of BOD that it consumes; a nutrient ratio 100: 10: 1 (BOD: N: P). Using COD; the ratio would be approx. 200:10:1 (COD:N:P)

This is very unlikely to occur in a wastewater composed entirely of domestic wastewater. Even in a wastewater containing 15 to 20% industrial content by volume, it is unlikely that nutrient imbalance will occur. In wine producing areas, where the industrial effluent contains a high COD with low nitrogen and phosphorus contents; nutrient imbalance can become a problem. In these cases, it may be necessary to add Urea or Limestone Ammonium Nitrate as a nitrogen source and phosphoric acid or Potassium Phosphate as a phosphorus source.

3.6.5 The Effect of Toxins.

If toxic substances are present, the entire relative predominance diagram will tend to be retarded with a greater effect on higher life forms such as stalked ciliates and rotifers. Depending on the nature and quantity of a toxic substance in the influent wastewater, the effect can vary from inhibition of the nitrification process to total process failure. The first effect will be noticed by an increase in effluent ammonia and the second by a RISE in dissolved oxygen content as the dying organisms are no longer able to process the wastewater. The effluent COD and suspended solids will also rise.

3.7 THE BIO-CHEMICAL PROCESSES IN WASTEWATER TREATMENT.

Up to this point, the relationship between the various types of micro-organisms involved in wastewater has been covered together with those factors that influence the treatment process. What has not been covered is who does what.

When referring to “Food” in earlier sections, one has really only considered the carbon based compounds whose content has been determined by the COD test. It is known that wastewater also consists of compounds containing nitrogen such as proteins, amino acids etc. The content of these is not measured in the COD test. One would use the Kjeldahl acid digestion test to determine the complex nitrogen containing compounds or the Free and Saline Ammonia test to measure the very simple ammonia containing compounds.

3.8 NITRIFICATION.

Nitrification was discussion in section 7.5 in PC Guide 3 and should be read together with this discussion.

As indicated in section 7.5; nitrification is a two-step process with ammonia first being oxidised to nitrite and then to nitrate.

There are a number of bacteria that perform the first reaction – these include: Nitrosomonas; Nitroscoccus; Nitrosospira and Nitrosolobus.

There are a number of bacteria that perform the second reaction – these include: Nitrobacter; Nitrospira and Nitrococcus.

The first step is “rate-Limiting”; this means that the overall rate of converting Ammonia into Nitrate is dependent on the rate of oxidation of Ammonia to Nitrite. This is why the Nitrite content of a wastewater under treatment or the treated effluent is usually very low.

The rate at which the nitrifying bacteria grow is much slower than the rate at which the “carbon” consuming bacteria grow. The breakdown of proteins and amino acids into simple ammonia containing compounds is generally quite quick.

Because the nitrifying bacteria grow more slowly, they held to be held in the system for longer. This means that the sludge age of a treatment works where nitrification is required (virtually all works these days), must be higher than if no nitrification was required. The nitrifying bacteria are also temperature sensitive. This means that a longer sludge age in required in winter than in summer.

If the sludge age is too short, the nitrifying bacteria will be removed from the system faster than they can grow and this will lead to process failure. To be sure of nitrification, the sludge age should preferably not drop below 14 days. Some researchers have quoted minimum sludge ages much shorter than this, but those would tend to be lab scale experiments.

In the nitrification process, ammonia is effectively converted into nitric acid. The oxidation of 1 mg of ammonia as N consumes 7.14 mg of alkalinity as $CaCO_3$. After complete nitrification, a residual alkalinity of 70 to 80 mg/L as $CaCO_3$ in the aeration tank is desirable.

3.9 DE-NITRIFICATION.

There are a large number of bacteria that are able to use nitrate as a source of oxygen when the mixed liquor does not contain any dissolved oxygen. They are known as facultative organisms. The part of the wastewater treatment works were nitrates are present but no dissolved oxygen is known as the anoxic zone.

The nitrate is reduced through a number of steps to nitrogen gas. Most of this will be lost to the atmosphere.

There are two main advantages of denitrification:

1. 1 mg of Nitrate as N contains just over 3 mg of Oxygen. If this oxygen could be re-used; then this would result in a saving in aeration costs – this is exactly what denitrification does;

2. It was noted above that the oxidation of 1 mg of ammonia as N consumes 7.14 mg of alkalinity as $CaCO_3$. Denitrification generates 3.57 mg of alkalinity as $CaCO_3$ for each mg of Nitrate as N denitrified. This is especially important where the alkalinity is low and could result in the pH dropping and affecting nitrification.

3.10 ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL.

Polyphosphate-accumulating organisms (PAOs) are a group of bacteria that, under certain conditions, facilitate the removal of large amounts of phosphorus from wastewater in a process, called **Enhanced Biological Phosphorus Removal (EBPR).** PAOs accomplish this removal of phosphate by accumulating it within their cells as polyphosphate. PAOs are by no means the only bacteria that can accumulate polyphosphate within their cells and in fact, the production of polyphosphate is a widespread ability among bacteria.

However, the PAOs have many characteristics that other organisms that accumulate polyphosphate do not have, that make them amenable to use in wastewater treatment. Specifically, this is the ability to consume simple carbon compounds (energy source) without the presence of an external electron acceptor (such as nitrate or oxygen) by generating energy from internally stored polyphosphate and glycogen and releasing the phosphate into the mixed liquor. Most other bacteria cannot consume the food under these conditions and therefore PAOs gain a selective advantage within the mixed microbial community present in the activated sludge.

It is therefore necessary for EBPR, wastewater treatment works to have an anaerobic tank (where there is no nitrate or oxygen present as external electron acceptor) prior to the other tanks to give PAOs preferential access to the simple carbon compounds in the wastewater that is influent to the plant.

After extensive research by the research group of van Loosdrecht and Heijnen in the Netherlands, Smolders et al (1994) presented a detailed metabolic model explaining the phenomena observed above on the level of cell microbiology. This is shown in figure 15 below:

PAO organisms contain three internal cell storage products relevant for enhanced phosphorus removal:

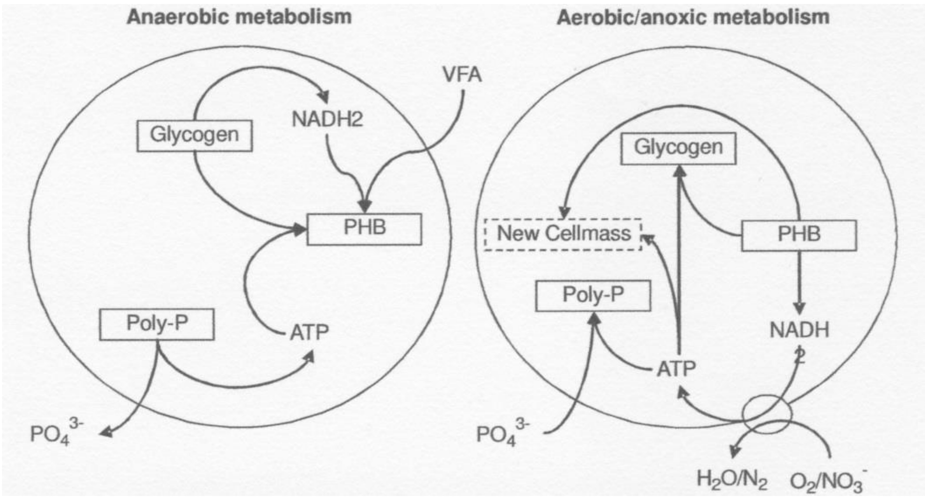
1. polyphosphate;

2. polyhydroxy-alkanoates (mainly present as polyhydroxy butyrate PHB);

3. glycogen. (this is a polysaccharide and consists of a number of glucose molecules connected together)

Under anaerobic conditions, volatile fatty acids are taken up from the liquid phase and stored as PHB. An important intermediate in this process is diHydro Nicotinamide Adenosine Dinucleotide ($NADH_{2)}$, an energy carrier released during the formation of PHB from glycogen. The energy required comes from the hydrolysis of polyphosphate and the subsequent formation of Adenosine TriPhosphate (ATP);

Under anoxic or aerobic conditions, the stored PHB will be oxidised to CO_2, releasing energy in the form of $NADH_2$. This will be used to create ATP, which in turn will allow the PAO organism to grow and restock with polyphosphate and glycogen. This process is graphically displayed in figure 15 below.



Smolders et al (1994)

Figure 15: SHOWING THE MAIN REACTIONS IN ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL.

The main difference between the metabolism of PAO under anoxic and aerobic conditions is the ratio between ATP formed/$NADH_2$ used: this ratio is about 40% lower under anoxic conditions. This explains the lower growth rate observed under anoxic conditions and also applies to “normal” heterotrophic organisms

A PAO related to the *Betaproteobacteria* has been identified and named Candidatus Accumulibacter Phosphatis. Accumulibacter has been shown to remove phosphorus from EBPR plants in Australia, Europe and the USA. It can consume a range of carbon compounds, such as acetate and propionate, under anaerobic conditions and store these compounds as polyhydroxyalkanoates (PHA) which it consumes as a carbon and energy source for growth using oxygen or nitrate as electron acceptor.

Recently, another PAO related to the *Actinobacteria* has been identified in wastewater treatment plants. These organisms appear to be limited to certain amino acids as carbon and energy source. The storage compound that they use to store the amino acids that these organisms take up under anaerobic conditions has not been identified. These bacteria have been observed in some EBPR plants in Denmark (where they were discovered) but their wider distribution is unknown.

There are a number of reasons why the enhanced biological phosphorus removal does not always take place. These include:

1. There may not be enough volatile fatty acids in the anaerobic zone for the bacteria. For convenience, their concentration may be indicated as COD. The commonly accepted figure is 25 mg/L COD. This is assumed to be SOLUBLE COD as it was shown earlier that bacteria can only metabolise soluble "food";

2. The Oxidation Reduction Potential may not be low enough due to the presence of Nitrates amongst others. A value of lower than -150mV is required;

3. The Glycogen Accumulating Organisms may be out-competing the PAO's. It appears that the PAO's prefer propionates over acetates as a volatile fatty acid source. There is much research ongoing in this field. It further appears that Glycogen Accumulating Organisms do not require phosphates in the production of Polyhydroxy Alkanoates.

THE PROCESS CONTROLLER's GUIDE TO

THE MICROBIOLOGY OF WASTEWATER TREATMENT

PART 4.

UNDERSTANDING THE BIOLOGICAL FILTRATION PROCESS.

4.1 INTRODUCTION.

Although the treatment of wastewater in biological filter is also performed by a number of different types of micro-organisms; there are some important differences.

While the activated sludge treatment process has a number of process variables that may be adjusted by the Process Controller, the biological filter has very few. This has the advantage of being simpler to operate. However, the effluent quality is generally not as good as that from a well operated activated sludge treatment works.

4.2 SUSPENDED GROWTH VERSUS ATTACHED GROWTH.

The micro-organisms involved in the treatment of wastewater by the activated sludge process are suspended in the liquid phase; as a result the process is described as 'Suspended Growth". In contrast, the micro-organisms in a biological filter are attached to the non-moving support medium – either stone or plastic; they are therefore described as "Attached Growth". Although, the support medium in a Rotating Disc Unit is moving; it should still be regarded as "Attached Growth" as the micro-organisms are attached to a solid medium – the disc.

4.3 THE MICRO-ORGANISMS INVOLVED IN THE TREATMENT BY A BIOLOGICAL FILTER.

As with the activated sludge process, there will be a number of different organisms involved in the treatment of the wastewater. There may be a slightly different relative predominance diagram. On the top of the medium there may often be algae present. There are usually more worms and even Psychoda larva/flies on the medium.

The bio-film that develops in a trickling filter may become several millimetres thick and is typically a gelatinous matrix that contains many species of bacteria, ciliates and amoeboid protozoa, annelids, round worms and insect larvae and many other micro fauna. Within the thickness of the biofilm, both aerobic and anaerobic zones can exist supporting both oxidative and reductive biological processes. At certain times of year, especially in the spring, rapid growth of organisms in the film may cause the film to be too thick and it may slough off in patches leading to the "spring slough".

The organisms that break off when pass out of the biological filter and will settle out the secondary sedimentation tank. In a biofilter works, this is traditionally called the humus tank.

In contrast to the activated sludge works, where the age of the sludge is accurately controlled; there is no such control facility in the biofilter process. For this reason, there is no such concept as "sludge age" here. In general, the "age" of the bio-mass being discharged from the biofilter is not known. As noted earlier, the sludge age in the activated sludge process is in reality an AVERAGE sludge age. When removed from the system; some sludge will be older than the average will some will be younger than the average.

The same applies to humus sloughed off the medium to which it was attached. Some of the material will be quite young while that part that was attached to the medium be older. In the absence of any definite information in this regard, it is assumed that an EFFECTIVE sludge age would be of the order of 5 to 10 days.

THE PROCESS CONTROLLER's GUIDE TO

THE MICROBIOLOGY OF WASTEWATER TREATMENT

PART 5.

THE ROLE OF THE PROCESS CONTROLLER IN THE ACTIVATED SLUDGE PROCESS.

5.1 INTRODUCTION.

It is known that with the exception of preliminary (and where used – primary treatment), the activated sludge process relies on various organisms to perform the treatment process. The treatment process consists essentially of 2 steps:

1. the first being where the micro-organisms utilise the incoming food to remove the influent COD by oxidation and incorporation into cell mass and convert nitrogen in nitrogen containing compounds into nitrates. Denitrification is then used to convert the nitrates into nitrogen gas;

2. the second being the separation of the micro-organisms by settlement for return to the first part of the process, leaving a clear treated effluent to be discharged.

It is the role of the Process Controller to manage the treatment process to allow the micro-organisms to perform their work optimally in both stages. As seen earlier, the Relative Predominance Diagram (figure 14) can assist the Process Controller in troubleshooting when problems develop in an activated sludge system. It was also previously noted that most of the micro-organisms can only be seen under a microscope.

This is where there is a major problem – very few Process Controllers have access to a microscope or to a laboratory that can perform a microscopic examination.

The Process Controller will have to use other methods of trying to assess the state of health of the micro-organisms and the effectiveness of the treatment process. It is important that the Process Controller have access to some chemical analyses. They can also make use of some physical tests to assist them in monitoring the treatment process and as a means of troubleshooting.

5.2 THE USE OF CHEMICAL ANALYSES FOR MONITORING AND TROUBLESHOOTING.

There are several chemical analyses that will assist the Process Controller. These are covered below.

5.2.1 The Chemical Oxygen Demand.

As the pollutional load of the wastewater and the quantity of "food" for the micro-organisms is measured by the Chemical Oxygen Demand (COD) test; this is the place to start. Hopefully the raw wastewater COD is measured on a composite sample so the Process Controller knows typical influent values. Combining with the daily flow, the Process Controller can know, log and track the daily influent load (kg COD/day) being received. If there are sudden increases or decreases, the Process Controller can be aware that process changes may have to be made. A sudden increase may result in increased aeration being required and an increase in sludge wasting. A sudden decrease in flow or load could mean a major sewer overflow upstream.

For a typical wastewater with up to about 15% industrial effluent content, the COD of the treated effluent should be less than about 60 mg/L. If higher than that, the test should be repeated with a filtered sample to see if the high COD is due to the suspended solids in the treated effluent.

5.2.2 The Ammonia Content.

It is known that the nitrifying bacteria are more prone to upsets and require a higher dissolved oxygen content to fully nitrify the influent ammonia. It is, therefore, necessary to monitor the ammonia content of the treated effluent. It is more useful to filter a sample of the effluent from the reactor and determine the ammonia content. This would give an earlier warning of an upcoming problem, than sampling the secondary sedimentation tank effluent. This is because the higher than normal ammonia content would be detected only a few hours later in the effluent from the secondary sedimentation tank.

The ideal situation would be an ammonia specific electrode at the reactor overflow weir giving a continuous read out, but very few treatment works would have such a facility installed.

5.2.3 The Oxidation-Reduction Potential.

In a similar manner to the pH value indicating how acid or alkaline a solution is; the oxidation-reduction potential indicates how oxidizing or reducing the solution is. An indication of the Oxidation-Reduction Potential for the various processes in wastewater treatment is given in table 1 below:

TABLE 1: SHOWING THE ORP FOR VARIOUS WASTREWATER TREATMENT PROCESSES.

Biochemical Reactions and Corresponding ORP Values

Biochemical Reaction	ORP, mV
Nitrification	+100 to +350
cBOD degradation with free molecular oxygen	+50 to +250
Biological phosphorus removal	+25 to +250
Denitrification	+50 to -50
Sulfide (H_2S) formation	-50 to -250
Biological phosphorus release	-100 to -250
Acid formation (fermentation)	-100 to -225
Methane production	-175 to -400

YSI

NOTE:

1. The 3rd line should read "Biological phosphorus **uptake**";

2. The anaerobic zone in an Enhanced Biological Phosphorus Removal treatment works would require an ORP of -100 to -250 mV.

From the table, it may be seen that higher positive values indicate a more oxidising medium while the lower more negative values indicate a more reducing medium. It is known that nitrification requires a higher dissolved oxygen content than for COD removal due to the requirements of the bacteria responsible for those reactions – this is clearly shown in the higher ORP requirement for nitrification.

A dissolved oxygen reading taken in an anoxic zone could indicate NIL dissolved oxygen, but this zone could contain nitrates that would mean that this is not a reducing medium as would be required for biological phosphorus release. The ORP meter would immediately indicate that this was not a reducing medium.

The oxidation – reduction potential is a useful tool for the Process Controller in ensuring optimum conditions for the wastewater treatment process. The dissolved oxygen meter can still be an important monitoring instrument in aerobic conditions.

5.2.4 Additional Test for Enhanced Biological Phosphorus Removal Works.

It was seen above that the oxidation-reduction potential in the anaerobic zone of an enhanced biological phosphorus removal plant should be in the range of -100 to -250mV. The real test is whether phosphorus is actually being released.

It is useful to determine the SOLUBLE phosphate content of the feed to and the effluent from the anaerobic zone. The effluent soluble phosphate content should be more than 50 mg/L as P. If this is not the case then there are two possibilities:

1. the oxidation-reduction potential is not low enough (not reducing enough);

2. the volatile fatty acid content of the feed to the anaerobic zone is not sufficient.

These two factors will be considered later.

5.3 THE USE OF PHYSICAL TESTS FOR MONITORING AND TROUBLESHOOTING.

It was noted earlier that there are basically two steps in the treatment process; namely the microbiological usage of the income food and the solids separation process to produce the clear effluent.

The physical tests below will examine the effectiveness of the separation process and the factors that affect it.

5.3.1 The Effect of Temperature on the Treatment Process.

In sections 2.11.6 and 2.12.1, the effect of temperature on the growth rate of the micro-organisms was noted. While the Process Controller has no influence on the temperature in the reactor, they can make process changes to allow for the variation in temperature during the year. This will be covered further later.

5.3.2 Factors Affecting the Settleability of the Activated Sludge.

Following the turbulence in the reactor that keeps the micro-organisms in suspension, the secondary sedimentation tank provides a still environment which allows the activated sludge to separate by flocculation and gravity sedimentation from the treated wastewater. This is intended provide a clear (low suspended solids (SS), low turbidity) overflow (the effluent) and a thick underflow (the return activated sludge (RAS)). For efficient treatment, both the aeration basin and the secondary clarifier must function satisfactorily. Therefore the solids separation phase is important in determining overall process efficiency.

There are basically two main types of several types of activated sludge solids separation problems:

1. Pin floc;

2. Filamentous bulking sludge.

A representation of these two types compared with an “ideal” floc structure is shown in figure 16 below:

Table 2 gives a summary of the causes and effects for the most commonly identified activated sludge solids separation problems.

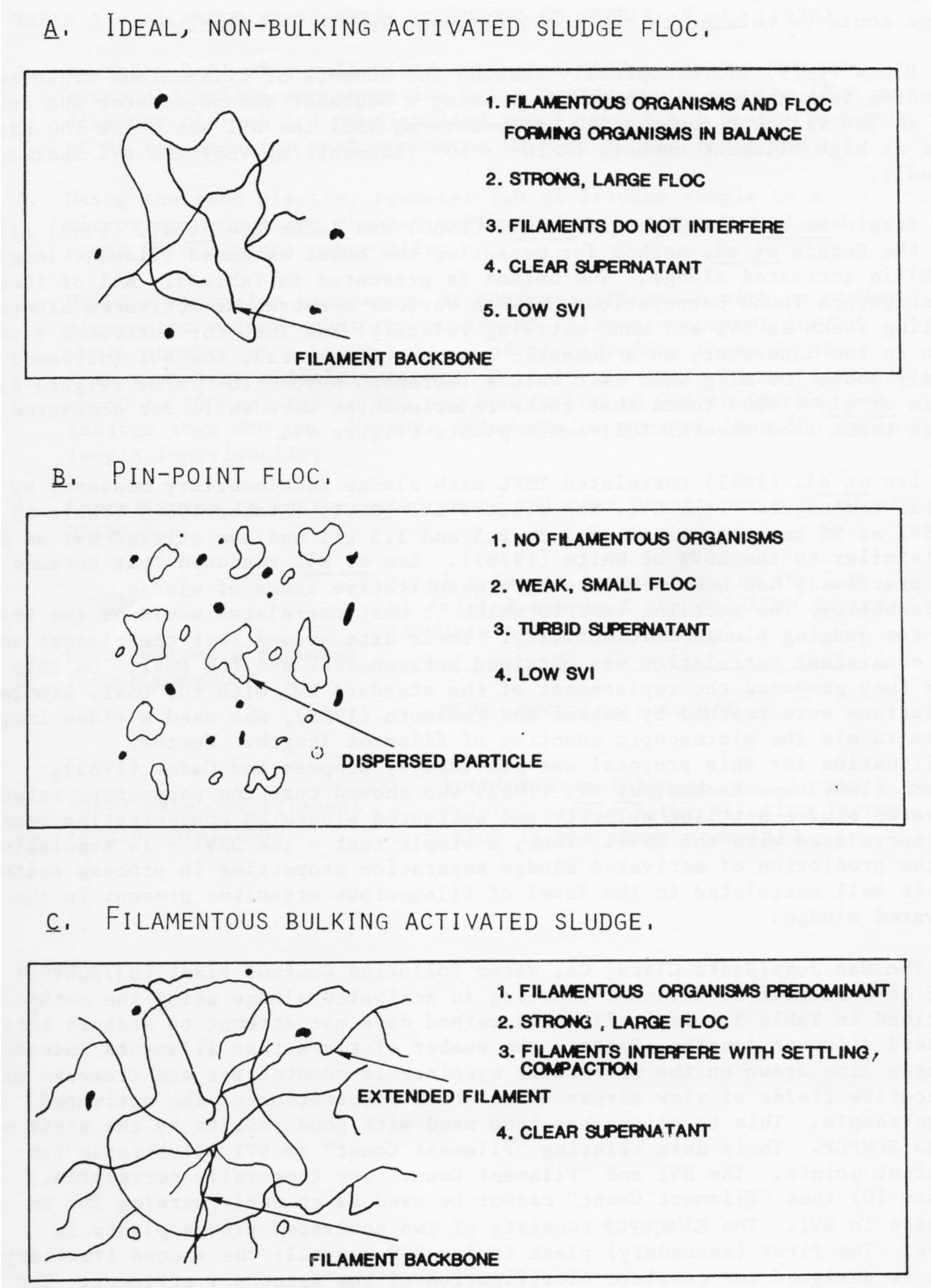


Figure 16: SHOWING VARIOUS TYPES OF STRUCTURE IN ACTIVATED SLUDGE.

(from Manual on the Causes and Control of Activated Sludge Bulking and Foaming – WRC)

5.3.2.1 Type A Activated Sludge.

This represents a good structure that contains a mixture of large flocs together with some filamentous organisms. The filamentous organisms with their long strands act in a similar way to polyelectrolytes in that they “hold” the flocs together by providing a support structure. This will produce a sludge with good settling properties and will produce a clear effluent. The sludge volume will range from about 50 to about 150 mL/gram

5.3.3.2 Type B Activated Sludge.

This represents Pin Floc (Pinpoint floc) where there is small weak floc with no filamentous organisms. This will be a population of suspended, growing, non-flocculated bacteria or fungi (most is bacteria). In a properly operating system, there will be some small separate bacterial particles present in the liquid around the floc. These dispersed bacteria are removed from the liquid as bacteria develop the "slime" layer and clump together to form floc. They are also removed by ciliates and rotifers. The presence of significant dispersed bacteria is due to improper floc formation. There are several reasons why floc does not form properly.

1. A young sludge.

   Referring to the Relative Predominance Diagram (figure 14), these sludges fall in area C. Here there is a lot of food still available. Bacteria are swimming and multiplying and are not forming flocs;

2. Toxicity/Lack of ciliates.

   Low levels of toxicity may kill most of the ciliates whose primary role is to remove the free-swimming dispersed bacteria;

3. A sudden increase in the amount of food.

   This will causes the bacteria to swim around and multiply quickly. The ciliate and other micro-organisms multiply more slowly and will take time to catch up to aid the formation of flocs;

4. Excessive shearing and /or high detergent loads.

   Excessive shearing will break up the floc. The same is true when polyelectrolytes are used for sludge conditioning and in water treatment. A high detergent load will prevent the "stickiness" of the bacteria and prevents them from clumping together to form floc.

The Pin Floc activated sludge will have a low Sludge Volume Index although some of the sludge will settle slowly due to the small particle size. There will be a turbid supernatant due to the lack of floc formation.

5.3.3.3 Type C Activated Sludge.

This represents the situation where the filamentous organisms predominate. There will generally be large strong floc that results in a clear supernatant on settling. The problem is that the relatively large number of filaments interfere with the settling and the compaction. The operational problem is that is usually that the retention time in the secondary sedimentation tank is too short – especially during high flow periods.

The Sludge Volume index can range from 200 to 400 mL/g or more. In many cases, there may be no settlement at all during the 30 minute settling test. Traditionally, if the volume of sludge after 30 minutes settling exceeds 400mL then the diluted SVI (DSVI) test must be used. Some references suggest that if the volume exceeds 200mL then the DSVI must be used.

For convenience, the procedure is repeated below:

After performing the standard SVI test and the volume exceeds 400mL (or 200mL as is sometimes suggested), then the mixed liquor must be diluted with SECONDARY SEDIMENTATION EFFLUENT either 1:1 or 1:2 (Mixed Liquor to Effluent) and the 30 minute test repeated.

EXAMPLE: If the mixed liquor is diluted1 part to 2 parts effluent (making a total of 3 parts) and the 30 minute settling test gives 200mL; then the DSVI = 200 * 3 = 600 mL/g.

5.4 CAUSES and EFFECTS of ACTIVATED SLUDGE SEPARATION PROBLEMS.

These are summarised in Table 2 below:

TABLE 2

CAUSES and EFFECTS of ACTIVATED SLUDGE SEPARATION PROBLEMS.

Nature of Problem	**Cause of Problem**	**Effect of Problem**
Pin Floc (Dispersed Growth).	Micro-organisms form small weak flocs, the larger of which will settle fairly well.	Turbid effluent due to poor settling of smaller particles.
Bulking.	Relatively too many filamentous organisms that extend from the floc into the bulk solution and interfere with compaction and settling of the sludge.	High SVI with a clear effluent if sufficient retention time in secondary sedimentation tank. Due to poor compaction, returned activated sludge concentration will be low. Can adversely affect sludge handling processes due to high volume to be discharged.
Sludge Blanket Rising.	Denitrification in secondary sedimentation tank releasing nitrogen gas that attaches to activated sludge particles causing them to rise to the surface.	Probable loss of sludge over outlet weir with adverse effect on effluent quality.
Foaming or scum formation.	Usually caused by Nocardia sp or Microthrix parvicella.	Foams float large amounts of activated sludge solids to the surface of the treatment units. The foam can be persistent and difficult to break mechanically. Probable loss of sludge over outlet weir with adverse effect on effluent quality.

5.5 THE NOCARDIA SCUM FORMING PROBLEM.

Floc-forming bacteria grow rapidly in the activated sludge system, peaking in number early in the process. Nocardia however, require a much longer time to grow from its early growth stage to fully branched filaments. In other words, the sludge age determines to a great degree whether or not Nocardia will remain in the early growth stage and cause no foam or if it will mature to fully branched filaments and consequently, cause foaming in the system. As long as the sludge age remains short enough, Nocardia will continue to exist as harmless, small cells.

The question is what causes all the foam on the tanks, in the wet wells and on the secondary sedimentation tanks? As long as the foam remains on the surface of the aeration basin, clarifiers and wet wells, Nocardia will continue its growth cycle. The foam, once accumulated, also provides a source of seed for Nocardia growth. So, the foam must be removed; sucked off or skimmed off, to prevent Nocardia from multiplying.

It is most important to not return the skimmed off foam back into the reactor. The problem is that the scum removed from the secondary sedimentation tank is usually discharged to the return activated sludge line. It needs to be removed from the system. Eliminating foaming problems caused by Nocardia will require time, patience and work. But it can be done. By decreasing the amount of time Nocardia remains in the aeration basin, one can prevent it from maturing into branching filaments and removing the foam from the system will prevent it from multiplying.

5.6 USING INFORMATION FROM ABOVE MONITORING TO MAKE PROCESS CHANGES.

5.6.1 Dissolved Oxygen Content

At the feed end of the reactor, the oxygen demand is very high and the micro-organisms responsible for COD removal will utilise all available dissolved oxygen. Proceeding along the reactor, this oxygen demand will drop. This will allow the dissolved oxygen to increase and at some point the dissolved oxygen will increase to a point where nitrification can begin.

If the zone of insufficient dissolved oxygen extends as far as the discharge from the reactor, then full nitrification will not occur. If this happens, then the Process Controller would need to increase the rate of aeration by switching on more aerators or blowers. If the dissolved oxygen remains low with all available aeration, then the total oxygen demand is too high.

The first thing to look at would be the sludge age. As micro-.organisms will continue to require dissolved oxygen even when no food is available, having too many in the system will create an unnecessarily high oxygen demand. As the sludge age increases, the amount of sludge produced per kg of COD received will **decrease**. This is as a result of endogenous respiration of the various organisms. This is shown in figure 17 below:

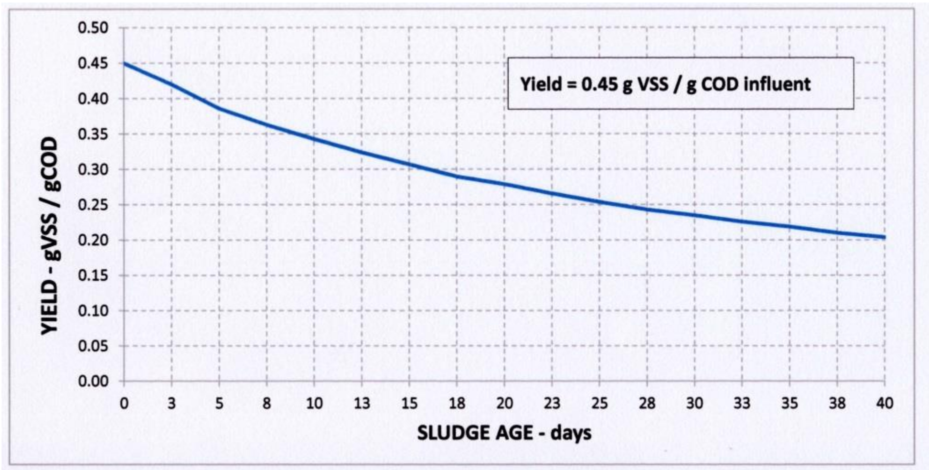


Figure 17 – SHOWING SLUDGE YIELD versus SLUDGE AGE.

However, the TOTAL mass of sludge in the system will **increase**, as will the oxygen demand of the mixed liquor. This is shown in figure 18 below. *(The 200 mg/L influent oxygen demand is used as an example – it will vary from works to works).*

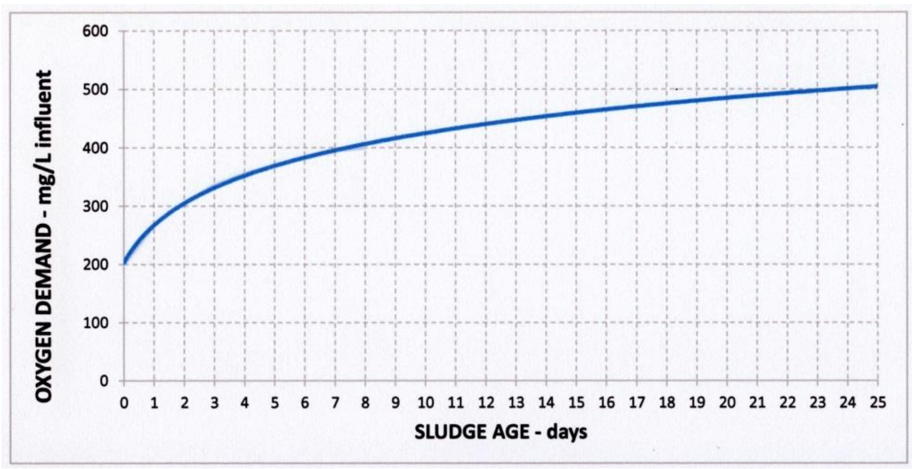


Figure 18 – AN INDICATION OF HOW TOTAL OXYGEN DEMAND WILL INCREASE WITH SLUDGE AGE.

There is another factor that the Process Controller must consider and that is the volume of mixed liquor to be wasted each day. How this volume of mixed liquor to be wasted varies with the sludge age is shown in figure 19 below:

Figure 19 – SHOWING VOLUME OF MIXED LIQUOR TO BE WASTED COMPARED WITH SLUDGE AGE.

As an example: the Process Controller decides that the low dissolved oxygen content of the mixed liquor is due to the mixed liquor concentration being too high. The plan would be made to reduce the mixed suspended solids by increasing the sludge wasting. The question is: what are the various impacts on the treatment works. These are summarized in Table 2 below:

TABLE 2 – SHOWING THE VARIOUS IMPACTS OF REDUCING THE MIXED LIQUOR CONCENTRATION.

DESCRIPTION	**IMPACT**
Oxygen Demand	Decreases
Electricity used for aeration	Decreases
Sludge Age	Decreases
Mass of sludge produced per unit of COD received	Increases
Mass of sludge to be wasted each day	Increases
Volume of mixed liquor (or RAS) to be wasted each day	Increases
Relative stability of wasted sludge	Decreases
Effect on F:M ratio	Increases
Potential for foaming problems	Decreases

This is where the Process Controller plays such an important role as they need to consider ALL the impacts of a process change.

5.6.2 Ammonia Content

As mentioned earlier, the nitrifying bacteria require a higher dissolved oxygen content in the reactor than do the other micro-organisms. Impact of this is that the first sign of a low dissolved oxygen content will be an increase in the ammonia content of the liquid leaving the reactor.

This will indicate to the Process Controller to increase the rate of aeration. If this is not possible, then the steps indicated in section 5.6.1 should be investigated.

5.6.3 Insufficient denitrification.

As mentioned earlier, denitrification will only take place under anoxic conditions – these are zero dissolved oxygen and an Oxidation-Reduction potential of less than 50mV. Unfortunately, most Process Controllers do not an ORP meters. If there is high nitrate content (more than about 3 mg/L) in the effluent from the anoxic zone, then the Process Controller should consider switching off one or two mixers for about an hour or so to allow anoxic conditions to develop.

The most likely factor that can prevent anoxic conditions developing in the anoxic zone is that the power input of the mixers is too high. This could allow air to be drawn into the liquid around the mixing shaft. This is in effect aeration of the liquid. Also too much mixing, means that there is more chance of oxygen being absorbed from the atmosphere by the rapid movement of the liquid in the anoxic zone. Generally only about 5W per cubic metre is sufficient to ensure adequate mixing;

5.6.4 Incomplete Phosphate Removal.

This section will only apply at wastewater treatment works designed for Enhanced Biological Phosphorus Removal. This is because an anaerobic zone at the head of the reactor is required. As mentioned in section 5.2.4; there are two main reasons for incomplete phosphate removal:

1. the oxidation-reduction potential is not low enough (not reducing enough). This could be due to nitrates being present in the recycled sludge flow. The ideal would be to have an Oxidation-Reduction Potential electrode in the anaerobic zone. This would quickly tell the Process Controller if the ORP fell in the required range. Failing this, it would be necessary to take a sample of the recycle sludge flow just before it enters the anaerobic zone to determine the dissolved oxygen and nitrate contents.

   The most cases the recycle to the anaerobic zone originates in the secondary sedimentation tank – the so called "S" recycle. This can contain nitrates. An improvement on this is to pump this recycle to the head of the anoxic zone and then pump some of the overflow from the anoxic zone to the head of the anaerobic zone. This is the so-called UCT modification and this recycle is known as the "R" recycle. This should contain very little nitrate.

2. the volatile fatty acid content of the feed to the anaerobic zone is not sufficient. As indicated earlier, the presence of volatile fatty acids are an essential source of food for the bacteria in order to release the phosphate. There is, unfortunately, not much that the Process Controller can do to ensure sufficient volatile fatty acids are present for the release of the phosphates. It may be possible to operate a primary sedimentation tank or primary sludge fermenter to increase the volatile fatty acid content of the feed to the anaerobic zone.

As mentioned in section 5.2.4, there is another group of organisms that complete for the volatile fatty acids as a source of food and these are the Glycogen Accumulating Organisms (GAO's). The conditions that favour the PAO's over the GAO's are not fully understood. It is thought that the presence of propionic acid (CH_3CH_2COOH) favours the growth of PAO's over GAO's.

5.6.5 The Effect of Temperature.

As the temperature of the contents of the reactor drops, the rate at which chemical and bio-chemical reactions slow down. As indicated earlier, the nitrifying bacteria are the slowest growing of the main organisms present in the wastewater treatment process. It is for this reason, that the minimum sludge age that a wastewater treatment works can be operated is dependent on the growth rate of the nitrifying bacteria.

The result of this is that the minimum sludge age will be longer in winter than in summer.

The saturation dissolved oxygen content of a liquid increases slightly as the temperature decreases. As the rate of aeration of the mixed liquor is dependent on the difference between the saturation dissolved oxygen content and the actual dissolved oxygen content, the efficiency of aeration will be slightly higher in winter than in summer – although the difference is small.

5.6.6 The Sludge Age.

The variation of sludge area is one of the most important process variables available to the Process Controller. A summary of the effects of a longer sludge age in given in table 3 below:

TABLE 3 – A SUMMARY OF THE VARIOUS IMPACTS OF A LONGER SLUDGE AGE.

PARAMETER CHANGE	IMPACT
Mixed Liquor concentration	Increased
Sludge mass produced per ML inflow	Reduced
Volume wasted per day	Reduced
Solids content of wasted sludge	Increased
Stability of sludge	Improved
Aeration requirement	Increased
Effect on Nocardia production	Worsens
Settleability of sludge	Will start to worsen at very long sludge age

5.6.7 Reducing the Impact of Nocardia Foam.

The presence of Nocardia in the activated sludge is not necessarily a problem, When the filaments grow longer and extend outside the sludge floc particles, then they become a nuisance. While the reason for problems with Nocardia foaming are not fully understood, there are some indications that the following may aggravate the situation:

1. a long sludge age. If possible the sludge age should be reduced;

2 a high oil and fat content of the influent wastewater. This might be due to certain industrial or commercial (restaurant) effluent. Those producers must have fat traps fitted and the fat must be moved and handled through the solid waste handling system;

3. higher temperatures. Unfortunately the Process Controller has no control over this aspect of the treatment process.

What is important,, is to remove the Nocardia foam. This is usually done through the scum scraper on the secondary sedimentation tank. It is very important that the removed scum NOT be returned to the reactor via the return sludge line. It must be removed to the sludge handling stream.

Some references suggest chlorination as a method to reduce the impact of the Nocardia on foam production. Other references indicate that the chlorination will have an adverse impact on the nitrifying bacteria.

Overall, the physical removal of the Nocardia remains the best alternative even though this can take several weeks of effective scum removal, to achieve the desired result.

5.6.8 Reducing the Impact of Filamentous Bulking

It was seen in section 5.3.2 that some filamentous organisms are important in assisting in the development of a compact, well settling sludge. Too few filaments and too many filaments, both have an adverse effect of sludge settleability and effluent clarity.

Under normal conditions in activated sludge, bacteria occur singly, in small chains or clumps. Under adverse conditions however, bacteria that grow filaments begin to form longer chains called filamentous bacteria. These filaments can dominate in the wastewater treatment system under a variety of conditions. These conditions are usually less favourable for the floc-forming bacteria so, this allows the filamentous organisms to gain an advantage. The presence of some filaments in the activated sludge is advantageous. They aid in settling by providing a “back-bone” for floc-forming bacteria to attach to. However, when filaments begin to grow in excess amounts, extending from the floc into the bulk fluid, they can interfere with settling and my cause foaming upon aeration. Different types of filaments dominate under different conditions. Identifying which filaments are dominating in the system will help the Process Controller to understand the condition in the treatment system so that corrective changes can be made. Microscopic evaluations to identify filamentous bacteria can be complicated and time consuming. In addition, these evaluations are generally not available to Process Controllers.

In general, excess filamentous bacteria growth is associated with a low dissolved oxygen content and long sludge ages (Low F:M ratio).

Septic wastewater with a high hydrogen sulphide content can encourage the growth of Thiothrix and Beggiatoa bacteria.

5.7 MICROSCOPIC EXAMINATION OF ACTIVATED SLUDGE.

As the environment in the aeration basin changes, one type of microorganism is replaced by another. The micro-organism best suited for the environment will emerge until the environment changes again. Changes in pH, dissolved oxygen, temperature, nutrients, competition etc., all determine which species will dominate. The protozoan species that are most dominant in the treatment system indicate which conditions are most dominant. Although, protozoan species dominance should not be relied on solely, to troubleshoot wastewater treatment conditions, this information is very helpful in assessing the conditions of the activated sludge process. This protozoan count procedure is not designed to determine the total number of each type of protozoan that is present in the system. Instead, what is important is the relative numbers of one type in comparison to another type. In other words, the purpose it to determine which species seems to be dominating. The count will examine protozoa in the following categories:

1. Amoebae
2. Flagellates
3. Free-swimming ciliates
4. Crawling ciliates
5. Stalked ciliates
6. Metazoa (rotifers, nematodes, water bear etc.)

In a well-operating system, the ciliates will most likely be the dominant species.

The microscopic examination of activated sludge is a complex subject and is usually not available to Process Controller due to the lack of suitable equipment.

Although activated sludge wastewater treatment is mainly a biological process, the Process Controller will need to rely on the various tests referred to earlier in order to optimise the treatment process.

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PART 6.

THE ROLE OF THE PROCESS CONTROLLER IN THE BIOLOGICAL FILTRATION PROCESS.

6.1 INTRODUCTION.

The Process Controller at a biological filtration wastewater treatment works has very few options available to them in respect of process control. The effluent quality is generally not as good as that from a well operated activated sludge plant. On the other hand, the effluent from an overloaded biological filtration works will generally not show the same deterioration in effluent quality as from an overloaded or poorly managed activated sludge works.

There are, however, a number of matters that will require the attention of the Process Controller. These are listed in the following sections.

6.2 THE NEED TO KEEP THE MEDIUM WETTED.

There are very few biological filters that are covered over. This means that the top layer of stone or plastic medium is open the sun and the wind; and can dry out if not wetted frequently. This would result in the biological growth attached to the top layer dying and falling (sloughing) off.

The recommended minimum wetting rate for a stone medium biological filter is 0.5 m^3 / m^2 – d. The maximum rate depends on media (stone or plastic) size and whether the biological filter is operated as a low rate or as an intermediate rate process unit. Where this minimum rate is not achieved during normal operation, a dosing syphon or a recirculation of humus tank effluent should be used. The Process Controller should be in a position to decide when to use recirculation of humus tank effluent.

The maximum time between each wetting period depends on a large number of factors and so a maximum time interval cannot be specified. It should generally not exceed about 15 minutes during the day and about 30 minutes during the night.

6.3 PROBLEMS WITH ROTATING DISTRIBUTOR SLOWING DOWN OR STOPPING.

If the rotating distributor slows down or stops, there are changes or adjustments that need to be made. These are given in below:

1. Increase hydraulic loading by recycling humus tank effluent. This may be necessary at periods of low flow, eg at night;

2. Close or block off certain of the reversing jets *(to stop the arms turning too quickly, usually one of the arms will have all the jets discharging in the opposite direction OR the arms will have a few jets discharging in the opposite direction)*;

3. Clogged jets may be the cause – this may be confirmed by checking the flow pattern from each jet. The remedy is to stop the distributor turning. There should be a fitting on each arm

and on various points on the biological filter wall to enable one to use rope the tie the arm to the wall fitting to stop the distributor turning. Then it will be safe to walk on the stone medium to clear the blocked jet;

.

4. The distributor arms may not be level. It is usually found that wire rope will start stretching a short time before it breaks. This would result in one or more arms sagging. The tension in the wire rope needs to be increased by tightening the turnbuckle. The clearance between the underside of the arm and the surface of the medium should be 15 to 22 cm. This is to allow for a suitable spray pattern from the jets.

   The turnbuckle and wire clamps should be wrapped with Denso Tape or similar material. ***Denso Tape***™ *is a cold-applied corrosion prevention and sealing* ***tape*** *based on a synthetic fabric, impregnated and coated with a neutral* ***petrolatum*** *compound.*

6.4 PROBLEMS WITH PONDING ON MEDIUM SURFACE.

Sometimes the wastewater applied to the surface of the biological filter does not drain into the spaces between the stones and forms a pond on the surface of the medium. This is known as "Ponding". There are a number of causes of ponding.

1. Blocking of the gaps between the stones by plastics and other materials that should have been removed by the screens in the preliminary treatment stage. The Process Controller needs to check that the screens are working effectively. Plastics etc will need to be removed after observing the standard operating procedure regarding the prevention of the turning of the distributor while working on the surface of the medium;

2. Blocking of the gaps between the stones by sludge carried over from the primary sedimentation tank. The Process Controller needs to ensure that adequate desludging of the primary sedimentation tank is taking place. It may be necessary to rake the surface of the medium to allow the ponded area to drain. Again the standard operating procedure, regarding the prevention of the turning of the distributor, must be observed;

3. Overloading of part of the medium due to blocked jets resulting in too much flow to parts of the medium. Cleaning of the jets as described in section 6.3 above is required;

4. Excessive biological growth may be taking place. It may be necessary to use a high pressure water jet to break up the solids to allow them to pass through the filter to the humus tank.

6.5 PROBLEMS WITH FLY BREEDING ON A BIOLOGICAL FILTER.

Sometimes fly breeding of Psychoda flies on a biological filter, can be a nuisance. There are generally two situations encouraging the breeding of the Psychoda fly. These are:

1. Construction of filters with open walls;

2. Use of a large size stone in the construction of the biological filter.

Both of these construction methods give rise to moist cavities where the mature insect can emerge from the pupa and where eggs can be laid without exposing the fly to currents of liquid which will drown it or wash it away.

As to differences in operation, deposition of excessive amounts of solids in the bed due to poor preliminary removal of suspended matter or to choking of surface layer by fungal growth, will encourage fly development. A very badly clogged filter, on the other hand, may so restrict passageways and so reduce dry surfaces in the filter that the flies have no suitable place to lay their eggs and fly emergence are rendered difficult. Fly breeding will then drop off. It seems, therefore, that both a seriously clogged filter on which ponding is frequently observed, and a relatively clean filter, may show quite low fly infestation.

Moderate populations are Psychoda flies are said to be important to the treatment process.. This is due to their grazing upon the zooglea which coats the filter substrate with the result that the zooglea is kept in a growth phase.

With moderate populations of Psychoda flies, the natural enemies of Psychoda such as birds; predatory flies, spiders etc will prevent excessive populations developing.

it appears that that the Psychoda favour larger stones, of greater than 5 cm in diameter, that provide spaces for the fly larva to develop.

Efficient distribution of liquid over the whole bed, through the installation of splash plates for example, allows for a more even wetting of the filter surface which can suppress fly emergence to a degree.

6.6 PROBLEMS WITH FLY BREEDING ELSEWHERE ON THE TREATMENT WORKS.

This will be as a result of poor housekeeping.

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PART 7.

MICROBIOLOGY OF WASTEWATER SLUDGE TREATMENT.

7.1 INTRODUCTION.

There are two sludge treatment processes that rely on bio-chemical processes to reduce the mass of sludge; produce a useful product or to stabilise the sludge. These are:

1. Aerobic process;

2. Anaerobic process.

7.2 AEROBIC PROCESSES FOR WASTEWATER SLUDGE TREATMENT.

This process may be thought of as simply increasing the sludge age of the waste activated sludge. It is usually referred to as 'Aerobic Digestion". As some of the micro-organisms die, they become food for other micro-organisms. The relative numbers of the various micro-organisms were seen in figure 14. The effect of treating the waste activated sludge by aerobic digestion is seen by moving further to the right in the Relative Predominance Diagram.

It will generally be necessary to allow for denitrification to prevent the pH dropping as a result of nitrification. In a surface aeration aerobic digester, this may be done by switching off aerators. This will not be possible with a fine bubble aeration system – here one would need a separate anoxic zone.

As shown earlier, some filamentous organisms are required to "hold" the sludge flocs together. As the sludge age is increased further (beyond about 35 days); one runs the risk of developing pin floc with its resultant poor settling characteristics.

It must be noted that aerobic digestion requires a lot of aeration and hence will have high electricity costs. For this reason, neither primary sludge nor humus sludge would be treated by aerobic digestion. This of course excludes the extended aeration activated sludge treatment works that does not have a primary sedimentation stage.

7.3 ANAEROBIC PROCESSES FOR WASTEWATER SLUDGE TREATMENT.

Anaerobic digestion involves several successive fermentations carried out by a mixed culture of microorganisms. This web of interactions compromises two general degradation phases: acid formation and methane production. Figure 20 shows, in simplified form, the reactions involved in anaerobic digestion.

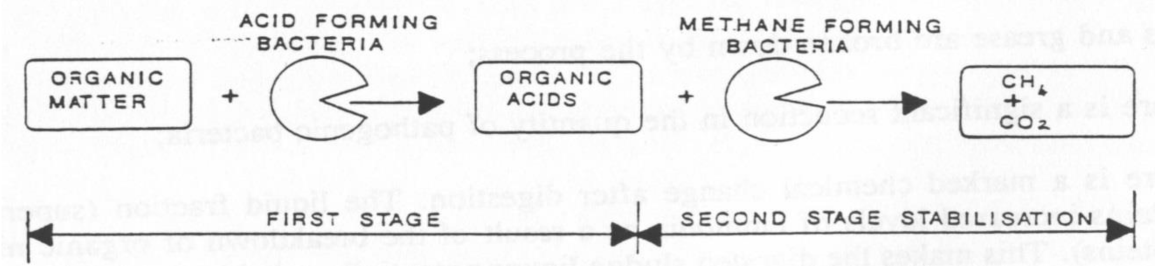

Figure 20 – A SIMPLIFIED ILLUSTRATION OF THE DECOMPOSITION OF ORGANIC MATTER INTO METHANE AND CARBON DIOXIDE.

In the first phase of digestion, facultative bacteria convert complex organic substrates to short-chain organic acids - primarily acetic, propionic, and butyric acids. These volatile organic acids tend to reduce the pH, although alkaline buffering materials are also produced. Organic matter is converted into a form suitable for breakdown by the second group of bacteria.

In the second phase, strictly anaerobic bacteria (called methanogens), convert the volatile acids to methane (CH_4), carbon dioxide (CO_2) and other trace gases. There are several groups of methanogenic bacteria each with specific substrate requirements that work together to reduce complex wastes such as wastewater sludge. Tracer studies indicate that there are two major pathways of methane formation:

1. The cleavage of acetic acid to form methane and carbon dioxide;

$$CH_3COOH \rightarrow CH_4 + CO_2$$

2. the reduction of carbon dioxide by hydrogen gas or formic acid (HCOOH) produced by other bacteria, to form methane.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

When an anaerobic digester is working properly, the two phases of degradation are in dynamic equilibrium; that is, the volatile organic acids are converted to methane at the same rate that they are formed from the more complex organic molecules. As a result, volatile acid levels are low in a working digester. However, methane formers are inherently slow-growing, with doubling times measured in days. In addition, methanogenic bacteria can be adversely affected by even small fluctuations in pH, substrate concentrations, and temperature. In contrast, the acid formers can function over a wide range of environmental conditions and have doubling times normally measured in hours.

As a result, when an anaerobic digester is stressed by shock loads, temperature fluctuations, or an inhibitory material, methane bacteria activity begins to lag behind that of the acid formers. When this happens, organic acids cannot be converted to methane as rapidly as they form. Once the balance is upset, intermediate organic acids accumulate and the pH drops. As a result the methanogens are further inhibited, and the process eventually fails unless corrective action is taken.

The anaerobic process is essentially controlled by the methane bacteria because of their slow growth rate and sensitivity to environmental change.

Therefore, all successful designs must be based around the special limiting characteristics of these microorganisms.

7.3.1 <u>The Effect of Temperature on Anaerobic Digestion.</u>

In the main wastewater treatment process, the Process Controller has no influence over the temperature at which the treatment works operates. In the anaerobic treatment of wastewater sludge, there are 3 main temperature ranges in which anaerobic digestion may be operated. These are:

1. cryophilic range 10 - 20ºC;

2. mesophilic range 30 - 40ºC;

3. thermophilic range 45 - 60ºC.

Volatile solids reduction is a good measure of the degree of stabilisation of wastewater sludge. It may be seen in figure 21 below how the rate and amount of volatile solids reduction is affected by temperature.

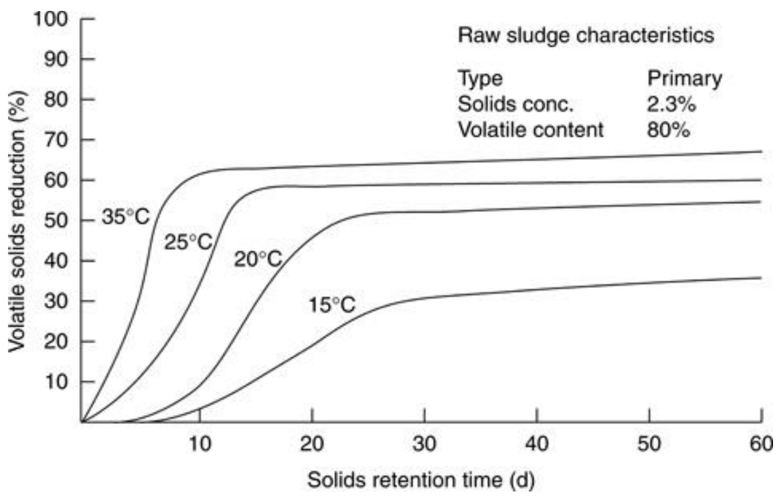

Figure 21: SHOWING RATE OF VOLATILE SOLIDS REDUCTION AT VARIOUS TEMPERATURES.

Within each operate mode, there is an optimum temperature of gas production. This is shown in figure 22 below:

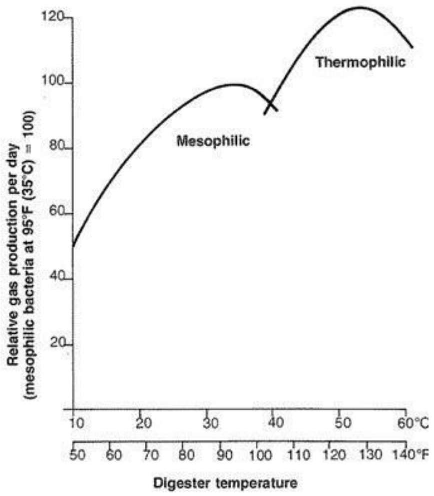

FIGURE 22: SHOWING OPTIMUM OPERATING TEMPERATURE.

As the anaerobic organisms, particularly the methanogens, are easily inhibited by even small changes in temperature, it is important that the temperature be kept as constant as possible. The temperature range should not be more than about 3ºC.

7.3.2 The Effects of Solids Retention Time on Anaerobic Digestion.

In order for the anaerobic digestion process to continue operating satisfactorily it is important that the bacteria have enough time to reproduce so that they can:

1. replace cells lost with the withdrawn sludge;

2. adjust their population size to follow fluctuations in organic loading.

In this respect a parameter called the solids retention time (SRT) is used, this is similar to the term sludge age as used in the activated sludge process. Often the term solids retention time is used in the latter process as well. In digesters where no recycle is used, the solids retention time is equal to the hydraulic retention time and is calculated by dividing the volume of the digester by the volume withdrawn each day. If a recycle of concentrated sludge is used (as in the activated sludge), the SRT increases relative to the HRT.

If the SRT falls below a critical value, the process will fail because the bacteria are being lost at a rate greater than they can reproduce. This is one of the reasons for ensuring that excessive quantities of water are not added to the digester with the feed sludge. This is apart from the extra heat needed for the excess water.

Typical Solids Retention Times for the various temperature ranges are shown in table 4.

TABLE 4 – TYPICAL SOLIDS RETENTION TIME OF DIFFERENT OPERATING REGIMES.

OPERATING REGIME	TYPICAL SRT
Cryophilic	30 to 60 days
Mesophilic	15 to 25 days
Thermophilic	5 to 12 days

Figure 21 shows that for each operating temperature range, there is a solids retention time beyond which there is minimal further volatile solids reduction.

7.3.3 The Effects of Mixing and Pre-thickening on Anaerobic Digestion.

The contents of a digester should be mixed continuously to create a homogeneous environment throughout the reactor. When stratification is prevented, the entire digester volume is available for active decomposition, thereby increasing the effective SRT. Also, what is most important, mixing brings the raw sludge into contact with the micro-organisms and evenly distributes metabolic waste products and any toxic substances present in the system.

It is important that sludge be thickened before being pumped to the digester. This is to reduce the volume of sludge to be handled. This is most important when heated digesters are used. If excessive quantities of water are added to the digester (in the form of a dilute sludge), there may be insufficient gas to provide the energy to heat the sludge to the desired operating temperature. This can result in the temperature of the contents of the digester dropping, this will result in less gas being produced and can lead to process failure.

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PART 8.

THE ROLE OF THE PROCESS CONTROLLER IN THE ANAEROBIC DIGESTION PROCESS.

8.1 INTRODUCTION.

The Process Controller has an important role to play in the monitoring and process control of the anaerobic digestion of wastewater sludge. As seen earlier, there are 3 possible operating modes for anaerobic digestion. The Process Controller is unlikely to have a choice as to which temperature range they wish to operate; this will usually be decided upon at the design stage. It is the role of the Process Controller to optimise the process to the best of their ability.

There are 3 main areas where the Process Controller has a major role to play:

1. Withdrawing of the sludge from the primary sedimentation tank and feeding the digester;

2. Controlling the operating temperature of the digester;

3. Withdrawing supernatant for return the head of the treatment works.

8.2 WITHDRAWING OF THE SLUDGE FROM THE PRIMARY SEDIMENTATION TANK AND FEEDING THE DIGESTER.;

Withdrawing the sludge from a primary sedimentation tank is an important process. This is usually done at regular intervals during the day and night. The Process Controller needs to ensure that sufficient sludge is withdrawn to prevent gassing and subsequent lifting of the sludge so that it is lost over the effluent weir. At the same time they need to ensure that only sludge is withdrawn and not water as well. Ideally digesters should be fed at a uniform rate but this is rarely the case.

Some treatment works have a gravity thickener into which the primary sludge is transferred. This makes it easier to feed the digester with a more uniform solids load.

By feeding a digester as frequently as possible, this helps to maintain constant conditions within the reactor. It also helps to equalize the gas production thus reducing wastage when the excess gas cannot be stored.

8.3 THE NEED TO CONTROL THE OPERATING TEMPERATURE OF THE DIGESTER.

This applies only to mesophilic and thermophilic operating modes. It was seen figure 22, that there is an optimum operating temperature, with gas production reducing both below and above this optimum temperature.

In the mesophilic operating mode, the feed sludge will be about 15 to 20º C cooler than the sludge in the digester. This means that the feed sludge will have a cooling effect on the contents of the digester. This is where the Process Controller plays an important role by:

1. feeding the sludge at as constant a rate as is possible and;

2. by limiting the volume fed to the digester by thickening the sludge as much as is possible.

8.4 WITHDRAWING SUPERNATANT FOR RETURN THE HEAD OF THE TREATMENT WORKS.

The supernatant from an anaerobic digestion system can contain high concentrations of organic material, both dissolved and suspended. Here the term supernatant refers to either liquid withdrawn from the upper layer of an unmixed digester or the liquid fraction from one of the dewatering processes that follows in digestion process.

The returning of supernatant to the usual treatment processes imposes an additional load that must be allowed for when determining the treatment capacity of the works.

As the organic materials in the supernatant are in a chemically reduced state, they will impose a large and often sudden oxygen demand. For this reason, the Process Controller should try to ensure that the supernatant is returned over as long a period as possible each day. During the normal biological process, phosphorus is removed from the water by the creation of new cell material, but during anaerobic digestion, cell material is broken up and the phosphorus is released. This release of phosphorus will reduce the overall removal and may necessitate the use of chemical treatment to remove the phosphorus to an acceptable level.

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