UNIVERSITY CURRICULUM DEVELOPMENT FOR DECENTRALIZED WASTEWATER MANAGEMENT

AEROBIC TREATMENT OF WASTEWATER AND AEROBIC TREATMENT UNITS

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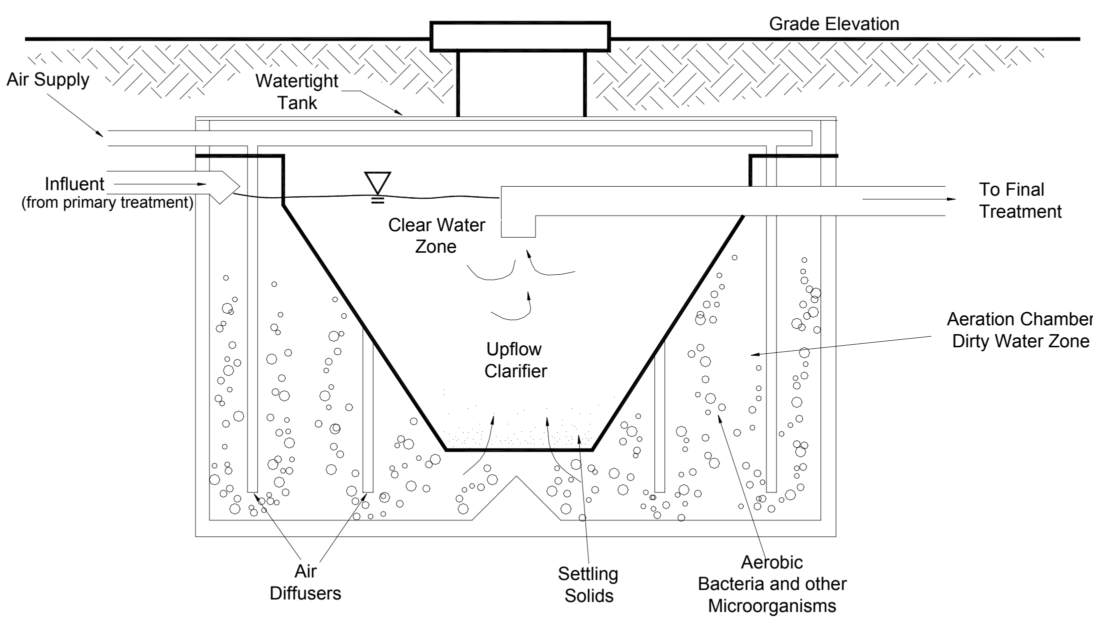

Acknowledgement

This work was supported [in part] by the National Decentralized Water Resources Capacity Development Project with funding provided by the U.S. Environmental Protection Agency through a Cooperative Agreement (EPA No. CR827881-01-0) with Washington University in St. Louis. The results have not been reviewed by EPA or Washington University in St. Louis. The view expressed in these materials are solely those of the NCSU, and University of Arkansas; EPA and Washington University in St. Louis do not endorse any products or commercial services mentioned in the materials.

Introduction

Naturally occurring microorganisms are the workhorses of wastewater treatment. Consisting of bacteria, fungi, protozoa, rotifers, and other microbes, these organisms thrive on many of the complex compounds contained in domestic wastewater. Secondary-treatment processes (found at municipal wastewater treatment plants) are highly engineered bioreactors. These bioreactors are designed to provide the microbes with the optimum conditions to assist in the renovation of domestic wastewater. With the mechanical addition of dissolved oxygen, aerobic and facultative microbes can rapidly oxidized soluble, bioavailable organic and nitrogenous compounds.

Onsite and decentralized wastewater management systems can also take advantage of this technology. Aerobic treatment units can be an option when insufficient soil is available for the proper installation of a traditional septic tank and soil absorption area. Increasingly, homes and small commercial establishments are being constructed in rural areas with no central sewer and on sites with marginal soils. In these situations, wastewater must receive a high-level of pretreatment before being discharged into the soil environment. Depending on local regulations, the use of an aerobic treatment unit may allow for reductions in the required infiltration area and/or reduction in depth to a limiting soil layer. This ability to produce a high-quality effluent may open sites for development that were previously unsuitable because of soil limitations (U.S. EPA, 2000).

Overall, the objectives of this module are to provide a review of the biochemical oxidation of soluble and colloidal organic compounds using aerobic microbial digestion, provide descriptions of various engineered systems that maintain high-rate digestion, and provide an understanding of the operation and maintenance required to keep these system functional. This module is divided into two sections: (1) the aerobic treatment process and (2) aerobic treatment units. Section one is a brief overview of the biochemical oxidation of soluble organic compounds found in domestic wastewater. The design of biological treatment units can be roughly divided into two categories: suspended-growth and attached-growth. The bio-processes used to convert organic carbon into inorganic carbon is the same in both categories. Citations are provided in the module to direct the reader to textbooks that can provide a more rigorous explanation about processes involved in biological wastewater treatment.

Section two describes the use of aerobic treatment units for decentralized wastewater management. While all wastewater treatment devices that are engineered to maintain aerobic conditions are considered aerobic treatment units, the community of onsite wastewater management professionals divide these devices into two classifications: saturated (with wastewater) and non-saturated. Whether suspended-growth or attached-growth, any unit that maintains saturated and aerobic conditions is generally referred to as an "ATU" - the acronym for aerobic treatment unit. The primary focus of this section is use of ATUs as an engineered, high-rate wastewater treatment process. In non-saturated attached-growth systems, atmospheric oxygen is passively transferred into solution as the water moves around or through the media. Trickling filters (such as those found at smaller municipal wastewater treatment plants) and most packed-bed filters typify this type of biological process. Non-saturated media filters are discussed in detail in the **Packed-Bed (Media) Filter Module**.

Section One - Aerobic Treatment Processes

Biochemical Wastewater Treatment

Most people consider bacteria and other microorganisms to be undesirable components of wastewater. In fact, only a small fraction of the microbes found in wastewater are truly pathogenic. Aerobic wastewater treatment encourages the growth of naturally-occurring aerobic microorganisms as a means of renovating wastewater. Such microbes are the engines of wastewater treatment plants. Organic compounds are high-energy forms of carbon. The oxidation of organic compounds to the low-energy form (carbon dioxide) is the fuel that powers these engines. Understanding how to mix aerobic microorganisms, soluble organic compounds and dissolved oxygen for high-rate oxidation of organic carbon is one of the fundamental tasks of wastewater engineers.

Natural Process

Microorganisms responsible for the oxidation of complex organic compounds are called "decomposers." They return the simple forms of carbon back to the soil, water and atmosphere. When high concentrations of organic pollutants are available, these decomposers flourish. Because these same microorganisms exist in natural water bodies, wastewater being discharged back into surface water bodies must have a very low organic strength. Natural aquatic systems must have an ample concentration of dissolved oxygen to support advanced life forms (i.e., fish, macroinvertebrates, and so on). Most decomposing microbes prefer aerobic conditions to anaerobic conditions. When dissolved oxygen is available, the aerobic decomposition of organic compounds consumes dissolved oxygen out of the water. If the rate of re-aeration is not equal to the rate of consumption, the dissolved oxygen concentration will fall below the level needed to sustain a viable aquatic system.

The concentration of soluble, bioavailable organic compounds in water is often measured as carbonaceous biochemical oxygen demand or cBOD. As described above, oxygen demand is the result of the aerobic microorganisms consuming dissolved oxygen as they decompose the organic carbon and nitrogenous compounds. In the engineered biochemical oxidation of wastewater, oxygen is supplied to the aerobic microorganisms so that they will consume the substrate (organic carbon) to fuel their metabolism. The result is the conversion of organic pollutants into inorganic compounds and new microbial cells. The net production of cells (creation of new cells versus the die off of old cells) will form an accumulation of biological material.

Typical organic materials that are found in residential strength wastewater include carbohydrates, fats, proteins, urea, soaps and detergents. All of these compounds contain carbon, hydrogen, and oxygen. Domestic wastewater also includes organically bound nitrogen, sulfur and phosphorus. During biochemical degradation, these three elements are biologically transformed from organic forms to mineralized forms (i.e., NH_3, NH_4, NO_3, SO_4, and PO_4).

Microbial Metabolism

Metabolism is the sum of the biochemical processes that are employed in the destruction of organic compounds (catabolism) and in the building up of cell protoplasm (anabolism). These processes convert chemically-bound energy into energy forms that can be used for life-sustaining processes. Catabolism is the oxidative, exothermic, enzymatic degradation process that results in the release of free energy from the structure of large organic molecules. Some of the released energy is available for the construction of new cellular material. Anabolism is a synthesis process that results in the increase in size and complexity of organic chemical structure (Benefield and Randall, 1985).

Fermentation and Respiration Aerobic and anaerobic heterotrophic microorganisms use the fermentation process to reduce complex organic compounds to simple organic forms. Heterotrophs are microorganisms that use organic carbon for the formation of new biomass. These organisms are consumers and decomposers, and therefore depend on a readily available source of organic carbon for cellular synthesis and chemical energy. They are the primary workhorses in the oxidation of soluble BOD in wastewater treatment. In comparison, autotrophic microorganisms can create cellular material from simple forms of carbon (such as carbon dioxide). These organisms are at the bottom of the food chain. They do not depend on other organisms for the creation of complex organic compounds. Autotrophic microorganisms are important for the removal of nitrogen from wastewater.

As shown in equation 1, fermentation is the exothermic, enzymatic breakdown of soluble organic compounds and does not depend on the presence of dissolved oxygen. The fermentation process is often described in two stages – acid fermentation and methane fermentation. End products of the acid fermentation process include volatile fatty acids (VFA) and alcohols. Little reduction in BOD occurs because the most of the carbon is still in an organic form. During methane fermentation, a portion of the acid-fermentation end-products are converted to methane and carbon dioxide gas. The result of this conversion provides a reduction in BOD. Anaerobic microorganisms are limited to the fermentation process. This is why methane can only be produced with anaerobic conditions.

Equation 1

$$\begin{matrix}\text{COHNS}\\ \text{organic compounds}\end{matrix} \xrightarrow[\text{microbes}]{\text{heterotrophic}} \begin{bmatrix}\text{volatile}\\ \text{fatty}\\ \text{acids}\end{bmatrix} + CO_2 + H_2O + CH_4 + \text{energy} + \text{residuals}$$

Through the process of respiration, aerobic microorganisms can further transform the VFA (and other bioavailable organic compounds) into carbon dioxide, water and additional energy (Lehninger, 1973). As shown in equation 2, respiration requires the presence of oxygen. Oxygen acts as an electron acceptor for the catabolic degradation of the VFA. Because aerobic microbes can readily convert bioavailable organic carbon into inorganic carbon, aerobic systems can provide high-rate wastewater treatment.

Equation 2

$$\begin{bmatrix}\text{volatile}\\ \text{fatty}\\ \text{acids}\end{bmatrix} + O_2 \xrightarrow[\text{microbes}]{\text{aerobic}} \text{energy} + CO_2 + H_2O + \text{residuals}$$

Biosynthesis According to Lehninger (1973), biosynthesis is the most complex and vital energy-requiring activity of all living organisms. As shown in equation 3, biosynthesis is the formation of characteristic chemical components of cells from simple precursors, and the assembly of these components into structures such as the membrane systems, contractile elements, mitochondria, nuclei, and ribosomes. Two kinds of ingredients are required for the biosynthesis of cell components: (1) precursors that provide the carbon, hydrogen, nitrogen, and other elements found in cellular structures, and (2) adenosine triphosphate (ATP) and other forms of chemical energy needed to assemble the precursors into covalently-bonded cellular structure.

Equation 3

$$\begin{matrix}\text{simple}\\ \text{precursors}\end{matrix} \xrightarrow[\text{energy}]{\text{microbes}} \begin{matrix}C_{60}H_{87}N_{12}O_{23}P\\ \text{new cells}\end{matrix}$$

As seen in equation 3, cell composition can be represented as $C_{60}H_{87}N_{12}O_{23}P$. If phosphorus is not considered, basic cell composition is often written $C_5H_7NO_2$. It is important to reinforce the point that the cellular components are being taken from the wastewater stream and thus, many of the wastewater constituents are being converted into new cells. Table 1 lists the typical composition of bacterial cells.

Table 1. Percent elemental composition of cellular material.

Carbon	50.0	Potassium	1.0
Oxygen	22.0	Sodium	1.0
Nitrogen	12.0	Calcium	0.5
Hydrogen	9.0	Magnesium	0.5
Phosphorus	2.0	Chlorine	0.5
Sulfur	1.0	Iron	0.2
Other trace elements including Zn, Mn, Mo, Se, Co, Cu, and Ni:	0.3		

Adapted from Metcalf and Eddy (2003)

Endogenous Respiration Under substrate-limited conditions, microbes will feed on each other at a higher rate than new cells can be produced. The aerobic degradation of cellular material is endogenous respiration (eq. 4). Endogenous respiration is not 100% efficient and thus there is an accumulation of slowly-degradable cellular material and other residuals (Reynolds ,1982). As will be described in Section Two, aerobic treatment units employed in the decentralized wastewater management industry operate in the endogenous respiration phase. Referred to as "extended aeration," this process provides plenty of aeration to ensure that once the food is consumed, the microbes will start feeding on each other. This effect minimizes the mass of accumulated biomass that must be removed by the maintenance provider.

Equation 4

$$\underset{\text{cellular material}}{C_{60}H_{87}N_{12}O_{23}P} + O_2 \xrightarrow[\text{microbes}]{\text{aerobic}} CO_2 + H_2O + PO_4 + NH_3 + \text{residuals}$$

Environmental Effects

In order to provide high-rate oxidation of organic pollutants, microorganisms must be provided with an environment that allows them to thrive. Temperature, pH, dissolved oxygen and other factors effect the natural selection, survival and growth of microorganisms and their rate of biochemical oxidation.

Temperature The rate of bio-oxidation is a function of temperature. Various microbial species have optimal temperatures for survival and cell synthesis.

- Psychrophilic microorganisms thrive in a temperature range of -2° to 30°C (28° to 86°F). Optimum temperature is 12° to 18°C (54° to 64°F).
- Mesophilic microorganisms thrive in a temperature range of 20° to 45°C (68° to 113°F). Optimum temperature is 25° to 40°C (77° to 104°F).
- Thermophilic microorganisms thrive in a temperature range of 45° to 75°C (113° to 167°F). Optimum temperature is 55° to 65°C (131° to 149°F).

Overall, as temperature increases, microbial activity increases. Generally speaking, decentralized aerobic treatment units are buried and the soil acts as a sink for the heat generated by the exothermic activity within the treatment unit. The microbial population in a buried aerobic treatment device will consist of a mixture of pshychrophilic and mesophilic organisms.

Food to Microorganism Ratio (F/M) This ratio represents the mass of bio-available organic compounds (substrate) loaded into the aeration chamber each day in relation to the mass of microorganisms contained within the aeration chamber. Typically this ratio is expressed in terms of mass of BOD per day per mass of microbes in the treatment unit (Crites and Tchobanoglous, 1998). The microbial population is dynamic and responds to changes in life-sustaining parameters. There are time lags to changes in the microbial population in response to sudden changes in organic loading. However, if all other factors are constant, the population can rapidly increase in response to an increased organic loading. To effectively treat the increased organic load, the hydraulic retention time of the basin must correspond to the time required for the population to increase. However, increased organic loading is often associated with increased hydraulic loading. If a means of flow equalization has not been provided, then effluent will not have the same residence time nor have been exposed to the same concentration of microbes.

Acid Concentration The influent pH has significant impact on wastewater treatment. Benefield and Randall (1985) report that it is possible to treat organic wastewaters over a wide pH range, however the optimum pH for microbial growth is between 6.5 and 7.5. It is interesting to note that bacteria grow best at slightly alkaline water. Similarly, algae and fungi grow best in slightly acidic water. The response to pH is largely due to changes in enzymatic activity.

Section Two - Aerobic Treatment Units (ATUs)

Aerobic treatment units are high-rate oxidizers of soluble organic and nitrogenous compounds. From a biological perspective, ATUs do not employ any new processes that are not already utilized in large-scale wastewater treatment plants. The technology that is unique to ATUs is the design and packaging of these systems for small flow situations. These devices are essentially miniature wastewater treatment plants. In addition to the reduction of BOD by aerobic digestion and the conversion of ammonia by nitrification, many commercially available ATUs have additional chambers that promote the removal of nutrients, suspended solids and pathogens from the effluent. Other unique aspects to the design of ATUs are the ease of installation at remote locations and the ease of maintenance for semi-skilled maintenance providers. ATUs installed at homesites and small commercial locations must be dependable and maintenance-friendly.

Process Description

Primary treated wastewater enters the aeration unit and is mixed with dissolved oxygen and suspended and/or attached microbes. The aerobic microbes convert organic compounds into energy, new cells and residual matter. As the water moves through the clarifier, a portion of the biological solids are separated out of the effluent and are retained within the ATU. The biological solids settle back into the aeration chamber where they serve as seed for new microbial growth. Settled biomass and residuals will accumulate in the bottom of the chamber and must be removed with periodic maintenance

Because the biomass creates an oxygen demand, clarification is an important part of generating a high-quality effluent. The soluble BOD of the effluent is generally below 5 mg/L, but the biomass solids carry over may produce an effluent BOD of 20 mg/L or greater (Benefield and Randall, 1985). Many ATUs have a conical-shaped clarifier to promote separation of the biomass. As the cross-sectional area of upflow increases, the fluid velocity decreases. Once the settling velocity of the biomass is greater than the fluid velocity, the biomass will no longer move upward. During periods of no flow, the biomass will settle back into the aeration chamber. Other

ATUs may incorporate inline filters to separate the biomass from the effluent. Such filters require periodic maintenance to remove the build up of solids.

In the aerobic process, organic nitrogen and ammonia are converted to nitrate. Under anoxic conditions (no molecular oxygen), the nitrate is denitrified to nitrogen gas. Some ATUs are designed to also provide denitrification as part of their operation. Design modifications include intermittently supplying air and recirculate the nitrified wastewater into the anoxic regions within the treatment unit. For more information on nitrification/denitrification, see the **Nitrogen Transformation Processes** Module.

Typical ATU Configurations

Most ATUs operate as an intermitted-flow, complete mix tank, constant volume reactors. The flow is intermitted versus continuous because influent is not continuous. The contents of the aeration chamber are thoroughly mixed to maximize the contact between dissolved oxygen, microbes and wastewater. Effluent moves out of the aeration chamber and into a clarifier. The rate of discharge is in direct response to the rate of inflow. The exception to this generalization is sequencing batch reactors. As described later in this section, this treatment device operates in batch mode.

Extended Aeration

Most commercially available ATUs operate as extended aeration units. Extended aeration is characterized by long-term aeration, long detention times, low food to microorganism ratio, and low biomass accumulation. As shown in figure 1, by providing plenty of dissolved oxygen and minimal soluble organic matter, the microbes will be in the endogenous phase of growth and will readily consume bioavailable organic carbon - including biomass. The goal is to balance the mass of new cells synthesized per day with the mass of cells endogenously biochemically-degraded per day. ASCE (1977) suggests that for a treatment unit to operate in extended aeration, 2000 cubic feet of air should be injected in the water per pound of BOD_5 removed.

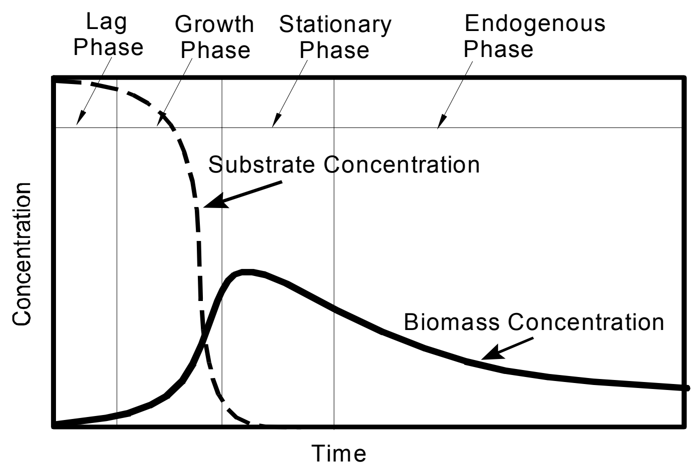

Figure 1. Kinetics of aerobic digestion: As substrate increases, biomass increases. These curves represent a "batch-style" application of substrate where biomass concentration changes in response to changes in substrate concentration. Intermitted-flow, complete mix systems only operate over a small range on these curves because the concentration of substrate tends to be relatively constant.

Suspended Growth Bioreactors

As shown in figure 2, suspended growth aerobic treatment units are scaled-down activated sludge plants. Activated sludge is a heterogeneous microbial culture composed mostly of bacteria, protozoa, rotifers and fungi. It is the bacteria that are responsible for assimilating most of the organic material, whereas the protozoa and rotifers (serving as predators) are important in removing the dispersed bacteria that otherwise would escape in the ATU's effluent (Benefield and Randall, 1985). The biomass is thoroughly mixed with the biodegradable organic compounds. Individual organisms clump together (flocculate) to form an active mass of microbes - biological floc (Davis and Cornwell, 1991). This slurry of biological floc and wastewater is called mixed liquor (Reynolds, 1982). The concentration of microorganisms in the mixed liquor is measured as the mg/L of mixed liquor volatile suspended solids (MLVSS).

Reynolds (1982) wrote that the term "activated" is used to describe the reactive nature of the biological solids. As wastewater enters the aeration chamber, the suspended floc adsorbs organic solids and absorbs soluble organic compounds. Through enzymatic activity, the organic solids are solubilized. Once in solution, the soluble organics are oxidized by biochemical

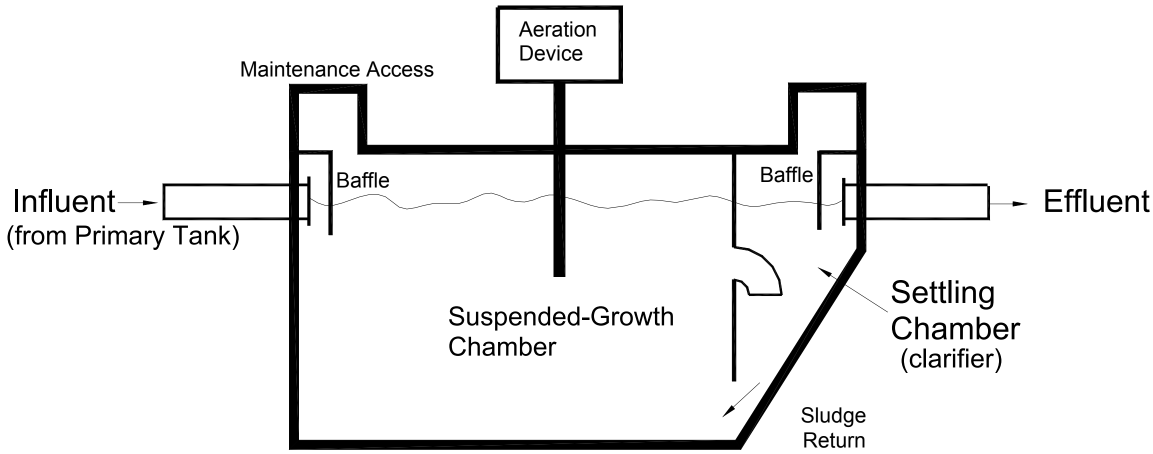

Figure 2. Schematic diagram of a suspended-growth ATU.

oxidation. At the inflow of the ATU, the capacity of the biological solids to adsorb and absorb substrate is rapidly filled. As the mixture moves toward the clarification zone, the biological solids (or "activated" sludge) are re-activated as the oxidation process proceeds. Near the downstream end of the ATU, the biological solids are substrate limited and are therefore highly reactive to the remaining suspended and dissolved organic solids. The extended aeration process has been shown to run properly at a food to microorganism ratio (F/M) of 0.042 to 0.153 pounds of BOD per pound of MLVSS. Functionally, the MLVSS should not fall below 2500 mg/L or exceed 6000 mg/L. The organic loading is typically about 15 pounds BOD per 1000 cubic feet of volume per day.

Attached-Growth Bioreactors

Another broad category of aerobic treatment is attached growth systems. Often called fixed-film reactors, an inert medium is provided for microbial attachment (fig 3). As the wastewater flows through (or across) the media, fine suspended, colloidal and dissolved organic solids are absorbed by the biological film. Wastewater and dissolved oxygen are brought in contact with the attached microorganisms by either pumping the liquid past the media or by moving the media through the liquid. Treatment units are available that are configured to combine attached-growth in the same basin as suspended growth. Referred to as "coupled-contact aeration," the

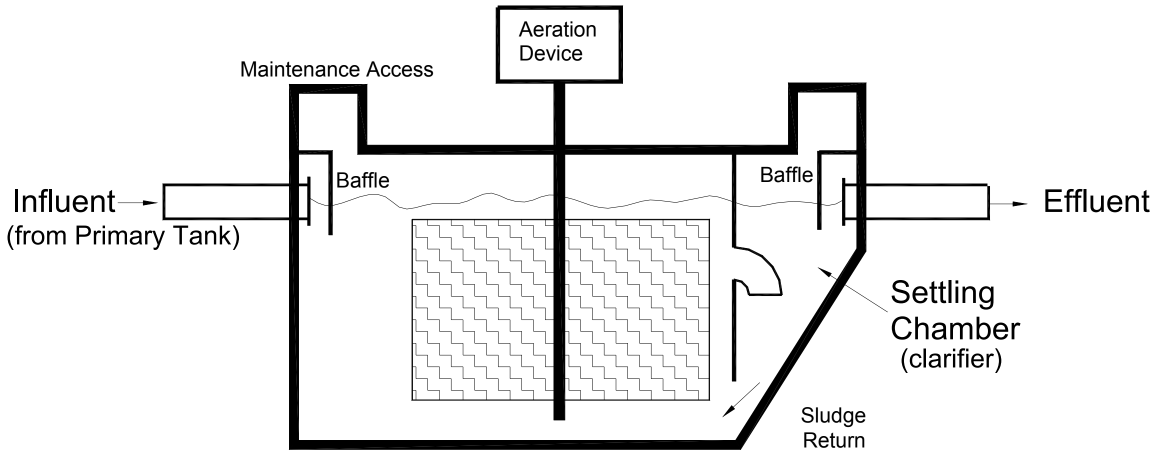

Figure 3. Schematic of ATU with submerged attachment sites provided for fixed-film growth.

combination of attached-growth and suspended growth processes enhances the performance and capacity of aeration units (U.S. EPA, 2002). This dual system approach provides a higher degree of microbial-population stability, and lower effluent suspended solids and BOD. Attached growth areas are submerged and large channels are provided for turbulent water to flow over the surfaces. These large channels allow suspended-growth microbes to flourish. Aeration is provided by directly injecting air and/or by circulating the water to the air-liquid interface. Excessive attached-growth will slough off and settle to the bottom of the chamber. These solids will accumulate and must be removed as part of periodic maintenance procedures.

Rotating Biological Contactor (RBC)

Rotating biological contactors combine suspended-growth and attached-growth bioprocesses. A series of closely spaced circular disks are mounted on a common shaft and are slowly rotated. The shaft is located either just above or just below the water surface. This location allows the surface of the disks to be exposed to both air and wastewater while rotating. A typical disk is made of an inert material such as polystyrene or polyvinyl chloride. A fixed-film biological growth attaches to the disks and when submerged, the organisms are exposed to food. In rotation, the reactor carries the fixed-film into the air and oxygen is absorbed. Excess dissolved oxygen mixes with the bulk liquid as the contactor surface moves back through the wastewater (ASCE, 1977). As the thickness of attached biomass on the disk increases, some of the excess biomass is sheared off the disk. This biomass is kept in suspension by the rotation of the disks. Ultimately, the flow of wastewater carries the solids out of the reactor chamber and into the clarifier.

Generally, about 35 to 45% of the disks' surface are submerged in a RBC that is designed with the shaft just above the water surface. A system that has the shaft submerged in the water produces about 70-90% submergence (Crites and Tchobanoglous, 1998). A higher degree of organic removal and nitrification may be obtained by arranging sets of disks (or other inert media) in series, since each subsequent stage receives an influent with a lower organic concentration than the previous stage. The tank construction is usually of reinforced concrete or steel, and is typically enclosed to maintain environmental controls and to confine any nuisance odors. Rotating biological contactors can be scaled down for single family homes or scaled up to provide secondary treatment at municipal wastewater treatment plants (Metcalf and Eddy, 2003).

Sequencing Batch Reactor Systems or Periodic Processes

In the sequencing batch reactor (SBR) system, flow equalization, aeration, clarification, and biomass wasting processes are carried out sequentially in the same tank (U.S. EPA, 1992). Since most SBRs require the system to be closed to influent during the treatment cycles, two reactors - that operate in parallel - are required in order to maintain continuous flow. However, with new inlet designs, single-tank reactors can be used to maintain continuous flow. The SBR process can provide flow equalization and tends to modulate the quantity and strength of wastewater inflow.

Process Description One cycle of SBR operation has five basic modes; fill, react, settle, decant, and idle.

- ***Fill*** Raw wastewater, that has been through primary treatment, is added to the reactor. During this phase, aeration may or may not be supplied to provide alternating periods of high or low dissolved oxygen. This mode may occupy 25% of the total cycle time.
- ***React*** Aeration is provided in an effort to obtain rapid biodegradation of organic and nitrogenous compounds. This mode will typically require about 35% of the total cycle time.
- ***Settle*** Aeration is shut off to allow the wastewater to become anoxic (for denitrification) and to allow for quiescent conditions that allow very effective liquid-solid separation. Clarification will usually take about 20% of the overall cycle time.
- ***Draw*** Clarified supernatant is removed. The decanting is accomplished using adjustable weirs, floating weirs, and submersible pumps. Periodically the excess biosolids must be removed. Decanting generally takes about 15% of the total cycle time.
- ***Idle*** Time is allowed for the first reactor to complete its full cycle, then switch the flow into the second reactor for parallel operation.

An important element in the SBR process is that a tank is never completely emptied, rather a portion of settled solids are left to seed the next cycle (Henry and Heinke, 1996). This allows the establishment of a population of organisms uniquely suited to treating the wastewater. By subjecting the organisms to periods of high and low oxygen levels, and to a high and low food availability - the population of organisms becomes very efficient at treating the particular wastewater (Henry and Heinke, 1996).

Nitrogen Removal in SBR During aeration, the organic and ammonia nitrogen present in the wastewater is converted to nitrate. When aeration is suspended and the remaining dissolved oxygen is consumed, denitrifying bacteria strip the oxygen out of the nitrate molecule, which converts nitrate to nitrogen gas (denitrification). While other ATUs can be designed to provide denitrification, the SBR sequence can provide denitrification conditions without adding on additional unit processes.

Typical Applications With the development of reliable automatic control systems, SBR package plants have become competitive with more traditional aerobic treatment units. The process is flexible and efficient, and can accommodate large fluctuations in hydraulic and organic loads. The process is particularly applicable to small communities, because of easy installation, simple operation, lower maintenance, and higher energy efficiency (U.S. EPA, 1992).

Proprietary Systems

The classical expectation of an ATU is to reduce the concentration of soluble organic compounds and suspended solids. Manufacturers of ATU's are actively developing new treatment systems that incorporate enhanced nitrogen and phosphorus removal, and disinfection as part of the treatment train. The technical aspects of these enhanced processes are discussed in detail in the **Disinfection** and **Nitrogen Transformation Processes** Modules.

Oxygen Transfer

In order to maintain aerobic conditions, large quantities of oxygen must be provided. If the influent to the ATU has an ultimate BOD of 100 mg/L, then 100 mg of dissolved oxygen per liter of influent must be provide in order to satisfy the oxygen demand. The primary function of the aeration system is to transfer oxygen to the liquid at such a rate that dissolved oxygen never becomes a limiting factor. Oxygen is only slightly soluble in water. Natural aeration cannot meet the demand of this high-rate unit process and therefore, oxygen transfer must be engineered into the treatment unit in order to maintain a minimum residual of 1 mg of dissolved oxygen per liter of water.

The passage of oxygen from the gas phase to the liquid phase is absorption. The driving force of oxygen transfer is the concentration gradient between the atmosphere and the bulk liquid. This gradient is created when there is a difference in the equilibrium concentration in the two phases.

Thus the desire to obtain equilibrium drives the transfer of atmospheric oxygen into the water. The saturated concentration of dissolved oxygen changes with temperature, barometric pressure, salinity, and with the concentration of water impurities. Designers of ATUs have to maximize the contact interface (surface area) between the gas and liquid phases in order to maximize the opportunity for oxygen transfer. In other words, systems must be designed so that the concentration gradient between the gas-liquid interface is high and therefore, the rate of transfer will be high.

Aeration units are evaluated on the mass of oxygen transferred per unit of air introduced to the water. This is an efficiency rating. The goal is to maximize the mass of O_2 transferred per unit of energy consumed by the device. The most common method of maximizing energy efficiency is to combine mixing with aeration. Turbulent mixing is required to maximize the opportunity for microbes to come in contact with both soluble organic compounds and dissolved oxygen. If steady-state conditions can be maintained, the rate of oxygen transfer is equal to the rate of consumption by the microorganisms. Dissolved oxygen in the mixed liquor needs to be maintained at 1 to 3 mg/L. For residential strength wastewater, Metcalf and Eddy (2003) report that 2 to 7 grams per day of dissolved oxygen are needed for each gram of MLVSS.

For most ATUs, the actual oxygen mass transfer efficiency is proprietary information. Manufacturers market specific ATU models based on organic and hydraulic loading. For a given unit, the aeration device is rated to provide sufficient dissolved oxygen for the given range of input oxygen demands (organic loading).

Basically, there are two types of aerators used by manufacturers of ATUs - diffused air systems and mechanical aeration systems. Diffused air systems use submerged devices (spargers) to inject air into the bulk liquid. As shown in figure 4, air injected below the surface has continuous contact with the liquid as it rises to the surface. The smaller the bubble, the greater the oxygen

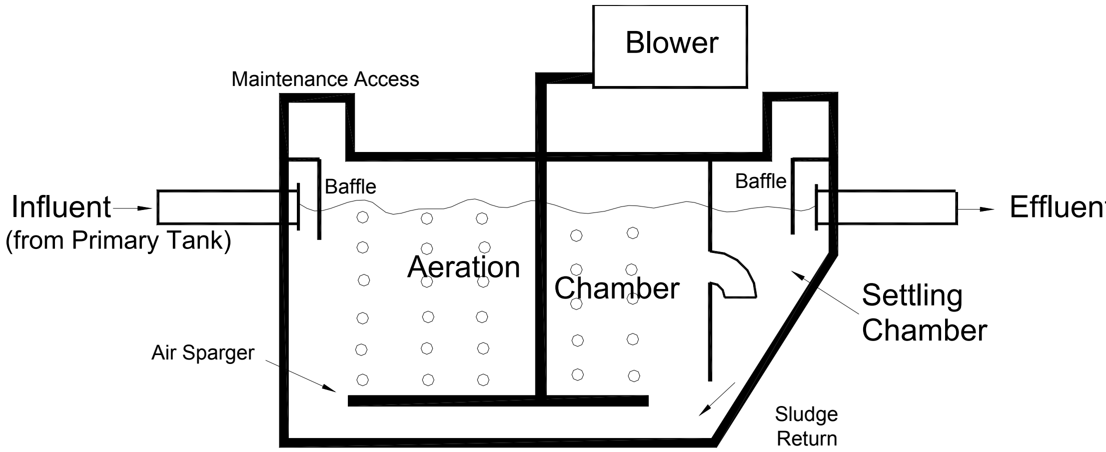

Figure 4. Example of diffused aeration using spargers to create small diameter bubbles.

transfer rate. Additionally, bubbles formed deep within the chamber will have more hydrostatic pressure to drive the oxygen transfer and more time-of-contact with the air-water interface. One method of creating small bubbles is with porous ceramic diffusers. The small-interconnected passageways inside the ceramic matrix create a tremendous loss of air pressure and many points of outflow. This combination produces streams of small bubbles over the surface of the ceramic diffuser. A second method of injecting air is to machine orifices into pipes and plates. Many large-scale aerobic digesters use jet aerators. Streams of air serve to transfer oxygen and to provide vigorous mixing of the basin contents.

A third type of diffuse aerator is an aspirated mixer. As shown in figure 5, a mixing-propeller is attached to a hollow shaft that is vented to the atmosphere. This paddle is located near the bottom of the aeration chamber. As the shaft spins, a venturi-type effect creates a vacuum down the shaft and injects air into the water.

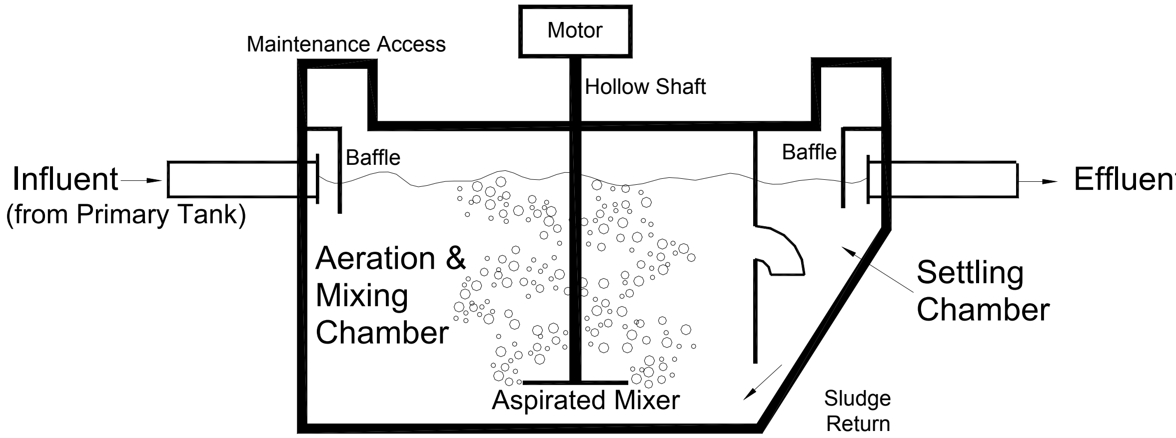

Figure 5. Aeration using an aspirated propeller and hollow drive shaft.

The mixing devices must balance the need for agitation while minimizing the shearing of floc. If shear is excessive, poor settling conditions in the clarifier can result.

Several ATU manufacturers employ a cycled-aeration approach. Cycling the aeration system provides some energy savings and promotes nitrogen removal (temporary anoxic conditions). Care must be taken, as this technique can produce a poor settling biomass due to gas flotation and non-flocculating microbes.

ATU Influent

Influent to the aerobic treatment chamber must first pass through primary treatment, provided by either a septic or some other type of primary tank. These tanks can provide separation of easily settable and floatable solids before the influent enters the ATU. A large portion of these solids are likely non-degradable or slowly degradable. Manufacturers of ATUs will provide guidance as to the size of a primary tank proceeding their aerobic treatment device. Primary tanks also provide an element of dilution to minimize the effects of chemical shocks to the microbial population in the ATU. Bleaches and other disinfectants must be highly diluted before entering the aerobic chamber. Medications, such as antibiotics and chemotherapy drugs, are highly toxic to the microbial population. Most manufacturers have a list of products that should not be added to the wastewater stream.

Hydraulic and Organic Loading

The specification of an ATU is based on both hydraulic and organic loading. Hydraulic loading is the rate that water will pass through the device and provides information about the length of time that wastes will be exposed to the microbes. For example, if the basin has a volume of 1000 gallons and the wastewater flow is 500 gallons per day, the hydraulic detention time is two days. Organic loading refers to the food (incoming colloidal and soluble BOD) as compared to the microbial population available to consume the food (F/M ratio). If there is more food than microbes, the effluent quality will be poor. If there are more microbes than food, then the effluent quality will be high. As previously mentioned, the population of microbes is dynamic in an ATU.

If the system has been upset due to heavy laundry water loads that are low in soluble BOD, the population may be reduced because of the lack of food. Additionally, wash-out of microbes can occur if the hydraulic loading is greater than the designed outflow rate of the clarifier. When the next heavy dose of organic material enters the tank, there may not be a sufficient microbial population to complete the digestion of BOD during the hydraulic detention period.

Flow Equalization

ATUs are designed to work within a range of hydraulic and organic loads. Variations in flow rates and constituent concentrations that are outside of the design specifications seriously complicate the treatment process. Municipal plants have the advantage of serving a large population, which tends to balance the daily organic and hydraulic loading. However, during storm events, municipal plants have to deal with tremendous inflow and infiltration problems. Often municipal plants will use offline equalization basin or bypass aerobic treatment in order to prevent the wash out of microbes. Likewise, residential ATUs systems must be designed to handle days with high flows and still be able to provide sufficient biochemical treatment to the discharged wastewater.

Ideally, flow equalization would dampen the variations, so that there would be a constant or near constant flow-rate into the ATU. Equalization can be achieved with storage, float switches, pumps, and timers. Generally, additional storage in the primary tank is the most cost effective method to accomplish flow equalization because tankage is usually the least costly portion of the overall expenses (Bounds, 2003). Most ATUs are not designed to provide flow equalization and therefore, equalization must be provided just prior to the ATU. additional information about designing for the daily variations in flow can be found in the **Hydraulics Module**.

Nitrogen and Phosphorus in Wastewater

Nitrogen present in wastewater results from the degradation of proteinaceous matter in feces and from urea, the chief constituent in urine. Nitrogenous compounds undergo various bio-transformations in response to the presence or absence of dissolved oxygen. The ATU influent, having just exited from a septic tank or other primary treatment, will have nitrogen in the organic or reduced-ammonium ion form. In the aerobic environment of the ATU, most of the ammonium will be oxidized to nitrate (NO_3), which is the most highly oxidized form. While in the aerobic treatment unit, a fraction of the nitrogen may be removed by sedimentation, volatilization, and denitrification. Unless process modifications are made to the ATU, no reliance on nitrogen removal can be expected. Nitrogen removal is very dependent on specific performance of individual ATUs to create denitrification conditions. The reader is encouraged to refer to the **Nitrogen Transformation Module** for a complete understanding of the conditions required to remove nitrogen from wastewater.

Because phosphorus is often a limiting nutrient in the natural ecosystem, eutrophication can occur when excess phosphorus is discharged to a surface water body. In wastewater phosphorus can be bound in organic compounds and/or can be in the soluble phosphate (PO_4) form. Typical phosphorus concentrations in septic tank effluent will range between 6-12 mg/L. Bacteria will assimilate a small portion of the orthophosphate during their growth process. Conceptually, this amount of phosphorous could be removed by sedimentation. Because residential ATUs operate in the endogenous phase, very little sludge wastage (and thus very little phosphorus removal) is provided. When a higher degree of phosphorus removal is needed, a more advanced wastewater treatment, such as chemical precipitation, will be required.

Operational Issues

Start Up

Start up involves the establishment of a sufficient population of microbes within the ATU to digest the soluble organic and nitrogenous components of the influent. In most applications, a sufficient population of microbes will enter the ATU with the wastewater to start the process. If needed, one method of inoculating the system is to add a few gallons of mixed liquor from an operational ATU. While the biomass concentration is increasing, the microbes tend to be dispersed and have not formed flocs that will settle in the clarifier. Until the biomass becomes more flocculated and can settle more readily, there is a greater potential for solids carry over especially with high hydraulic loads. If solids are allowed to build up in the clarifier, gas will form in the biosolids (from anaerobic conditions within the solids) and cause solids to rise to the surface and form a scum layer. A good measure of how well the process is proceeding is by judging the quality of the activated sludge. Generally, good quality activated sludge will have a golden brown color, and an earthy smell if kept aerated.

Typical Problems

Sludge bulking is a phenomenon that develops in the aeration tank when a growth of a filamentous bacteria, primarily *sphaerotilus*, attach to the floc particles and impede settling (Crites and Tchobanoglous, 1998). Such microorganisms can tolerate large changes in dissolved oxygen and nutrients, a situation frequently occurring in small aerobic treatment units. When these conditions occur, it leads to carryover of solids in the effluent. This phenomenon is particularly troublesome to smaller plants where there may be considerable fluctuation in organic loading and lack of technical support.

When an excessive growth of *nocardia* (a hydrophobic bacterium) occurs, foaming and frothing on the liquid surface in the aeration chamber (and the clarifer) may result. The problem is exacerbated by the fact that the baffles in the clarifier trap the foam and foster more growth (Crites and Tchobanoglous, 1998). Some ATU manufacturers provide froth spray pumps. The froth spray serves to reduce the surface tension of the water and break down the froth (OhioEPA, 2000).

Biomass (Sludge) Wastage

Although ATUs use the extended aeration process, endogenous degradation cannot completely prevent accumulation of old biomass. Biomass and non-biodegradable solids will accumulate in a low area of the ATU, and periodically, a maintenance provider must remove a portion of these solids. During removal, it is important to leave some of the solids in the aerobic chamber to serve as seed to repopulate the biological floc.

Performance Certification

NSF International and the American National Standards Institute publish a standardized procedure for independent evaluators to certify the performance and reliability of aeration units. NSF/ANSI Standard 40-2000, Residential Wastewater Treatment Systems, establishes minimum materials, design and construction, and performance requirements for residential wastewater treatment systems having single, defined discharge points and treatment capacities between 400 and 1500 gallons per day.

Mechanical Evaluation

Design and construction requirements of this standard ensure that the structural integrity is maintained when the system is subjected to earth and hydrostatic pressures. An *in situ* visual evaluation of the structural elements is performed during and after the performance testing period. The system is tested to ensure it is watertight (i.e., no infiltration of groundwater or exfiltration of wastewater). Watertightness is evaluated by filling the tank with tap water to the level of the high-level alarm. This level is then monitored for 24 hours.

All ATUs have moving parts. These parts operate in very corrosive environments and therefore require periodic maintenance and/or replacement. During the certification procedure, all the mechanical components are evaluated to determine the frequency of required maintenance and the ease by which the maintenance can be performed by the service provider. Inspections are conducted to ensure that all electrical components are protected by safety devices that meet or exceed Standard ANSI/NFPA 70. ATUs must have mechanisms or processes capable of detecting failures of electrical and mechanical components that are critical to the treatment processes and/or detecting high water conditions. These mechanisms must be capable of delivering a visible and audible signal to notify the owner when an electrical, mechanical, or hydraulic malfunction occurs.

All units must have ground-level access ports for visual inspection, periodic cleaning, replacement of components, removal of residuals, and sampling. Access to ports must be protected against unauthorized intrusions via padlocks, covers requiring the use of special tools, or a cover weighing a minimum 65 pounds.

Performance Evaluation

Performance testing and evaluation of a specific type/model of treatment system is conducted for 26 consecutive weeks, 16 weeks of design loading followed by 7.5 weeks of stress loading and another 2.5 weeks of design loading. Design loading consists of operating 7 days per week with a wastewater volume equivalent to the daily hydraulic capacity of the unit. The 30-day average carbonaceous BOD_5 ($CBOD_5$) and total suspended solids (TSS) concentrations of wastewater entering the system should range between 100-300 mg/L and 100-350 mg/L, respectively. Stress loading is designed to simulate four non-design conditions: laundry day, working parents, power or equipment failure, and vacation.

Performance testing and evaluation is conducted during 96 data days with no interruptions for routine service or maintenance. Unless otherwise specified, all sample-collection and analysis methods must be in accordance with the current edition of the American Public Health Association's Standard Methods for the Examination of Water and Wastewater. During periods of design loading, daily composite effluent samples are collected and analyzed five days per week. During stress loading conditions, influent and effluent 24-hr composite samples are collected on the day each stress condition is initiated. Afterwards, samples are taken to monitor the recovery of the treatment unit. Twenty-four hours after the completion of the wash day, working-parent, and vacation stresses, influent and effluent 24-hr composite samples are collected for six consecutive days. Forty-eight hours after the completion of the power/equipment failure stress, influent and effluent 24-hr composite samples are collected for five consecutive days.

Residential wastewater treatment systems are classified as either Class I or Class II according to the chemical, biological, and physical characteristics of their effluents. A Class I certification indicates performance to EPA Secondary Treatment Guidelines for three parameters – $CBOD_5$, solids, and pH. (U.S. EPA, 1996) During the first calendar month of performance testing and evaluation, a unit is allowed to exceed 1.4 times the effluent limits for $CBOD_5$ and TSS sample concentrations without losing Class I status. A system can be designated Class II if 10% (or less) of their effluent $CBOD_5$ and TSS sample concentrations are greater than 60 mg/L and greater than 100 mg/L, respectively. Table 2 provides the criteria for Class I and Class II performance standards.

Table 2. NSF/ANSI Standard Number 40-2000 performance classifications.

Parameter	30 day average shall not exceed	7 day average shall not exceed
Class I		
$CBOD_5$	25 mg/L	40 mg/L
TSS	30 mg/L	45 mg/L
Color	Individual samples shall be less than 15 NTU units.	
Threshold Odor	Non-offensive	
Oily Film	None visible other than air bubbles	
Foam	None	
pH	The individual effluent samples shall be between 6.0 and 9.0	
Class II		
Not more than 10% of the effluent BOD_5 values shall exceed 60 mg/L and not more than 10% of the effluent TSS values shall exceed 100 mg/L.		

As shown in table 2, the performance bases of NSF/ANSI Standard 40 are organic carbon and suspended solids in the effluent. There is increased interest in evaluating treatment units for their capacity to remove nitrogen, phosphorus, and pathogens. Standard 40 provides procedures for the evaluation of the removal of these constituents. However, specific performance of the removal of these constituents is not required in order to receive certification (Converse, 2001). The primary function of saturated, aerobic treatment units is the digestion of soluble and colloidal organic compounds and removal of solids. Additional unit processes are added to the treatment train to provide denitrification, phosphorus removal, and disinfection.

Summary

Aerobic treatment units can provide rapid oxidation of soluble organic compounds, nitrification of ammonia, and reduction of suspended solids. These systems are utilized to provide a high quality effluent in situations where the natural surrounding has limited ability to renovate domestic wastewater. Whereas ATUs can effectively oxidize organic compounds and remove suspended solids, the accumulation of these wastewater constituents must be managed as part of a regularly scheduled maintenance procedure. It is highly recommended that aerobic systems include communication technologies that can notify maintenance provider in case of equipment failure. If an aeration unit goes down, it is only a matter of a few hours (depending on the organic loading) before the unit becomes septic. Maintenance should be provided by personnel trained by the manufacturer to ensure long-term success of the system.

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