SMALL SCALE WASTE MANAGEMENT PROJECT

Selected Definitions Associated with On-Site with On-Site Treatment with Emphasis on Aerobically Treated Wastes

by

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SELECTED DEFINITIONS ASSOCIATED WITH ON-SITE TREATMENT

WITH

EMPHASIS ON AEROBICALLY TREATED WASTES

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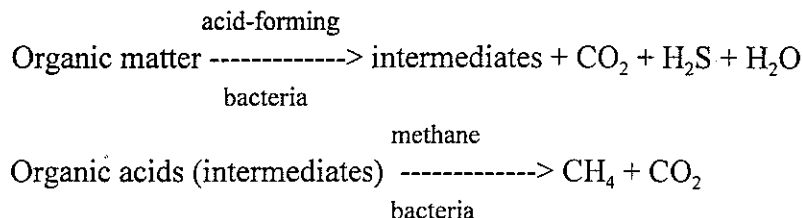
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The following definitions are associated with wastewater treatment with emphasis on aerobically treated effluent. The list is not inclusive but should assist the reader in better understanding the concepts associated with treating the wastewater aerobically.

1. Anaerobic Biological Process

The anaerobic biological process is a two-step liquefaction/gasification process occurring in the absence of oxygen. Two groups of heterotrophic bacteria (those obtaining carbon from organic compounds) convert the organic matter in wastewater initially to intermediates (partially stabilized end products including organic acids and alcohols) and then to methane and carbon dioxide gas through the simplified process as follows:

$$\text{Organic matter} \xrightarrow[\text{bacteria}]{\text{acid-forming}} \text{intermediates} + CO_2 + H_2S + H_2O$$

$$\text{Organic acids (intermediates)} \xrightarrow[\text{bacteria}]{\text{methane}} CH_4 + CO_2$$

The anaerobic digester, used primarily for solids stabilization in municipal systems, is heated at 35° C for approximately 30 days to reduce the volume by about 30% and putrescibility (odor reduction) which simplifies disposal. Advantages of anaerobic processes are the production of useful energy (methane) and lack of solids production which is only about 10% of that from aerobic processes. Obviously, septic tanks do not meet these environmental conditions and treatment is incomplete. However, septic tanks produce some methane and carbon dioxide but the scum and sludge are not stabilized significantly.

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Note: The materials presented in this document were primarily extracted from several documents listed in the reference list.

Anoxic Process

Under anaerobic conditions, compounds such as nitrate and sulfate (where oxygen is bound and not in molecular form) are reduced to nitrogen gas (anaerobic denitrification) and hydrogen sulfide gas by heterotrophic bacteria as per the following processes. This process is sometimes referred to as the anoxic process.

$$NO_3^- \xrightarrow[\text{bacteria}]{\text{denitrifying}} NO_2^- \longrightarrow N_2O \longrightarrow N_2 \text{ (anaerobic denitrification)}$$
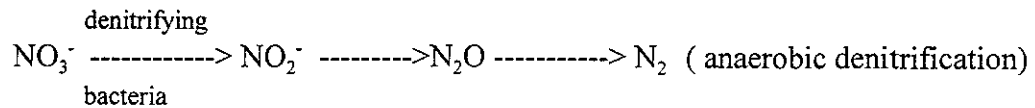
Any sulfates will be reduced to odorous hydrogen sulfide gas as per:

$$SO_4^{-2} \xrightarrow[\text{bacteria}]{\text{sulfate reducing}} H_2S$$
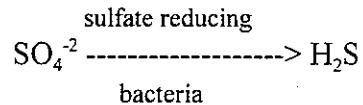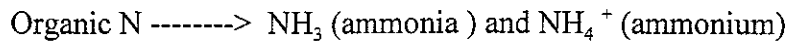
2. Aerobic Biological Process

The aerobic process occurs in the present of molecular oxygen by heterotrophic bacteria. The bacteria convert about 1/3 of the colloidal and dissolved organic matter to stable end products (carbon dioxide and water) and about 2/3 into new microbial cells.

The first step is:

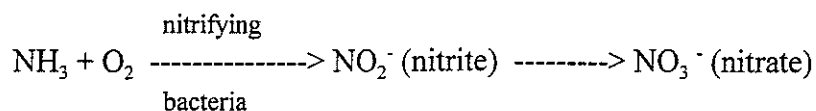$$\text{Organic matter} + O_2 \longrightarrow CO_2 + H_2O + \text{new cells}$$
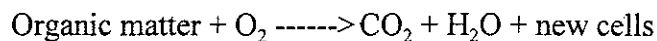
Autotrophic bacteria (those obtaining carbon from inorganic compounds) convert the nitrogen in organic compounds to nitrates in a two-step process as per (simplified):

Ammonification Process

$$\text{Organic N} \longrightarrow NH_3 \text{ (ammonia) and } NH_4^+ \text{ (ammonium)}$$

Nitrification process

$$NH_3 + O_2 \xrightarrow[\text{bacteria}]{\text{nitrifying}} NO_2^- \text{ (nitrite) } \longrightarrow NO_3^- \text{ (nitrate)}$$

A balance of essential nutrients is normally presence in domestic and municipal wastewater. However, in many industrial wastewaters, sufficient nutrients, such as

nitrogen and phosphorus may not be present. The process is relatively simple, stable , efficient and odor free with rapid conversion of organic matter to bacterial cells.

The systems can be divided into two types, namely suspended-growth and fixed film processes.

a. Suspended-Growth

Microorganisms are kept in a suspension in an aeration tank where air is mixed with the wastewater. The bacteria convert the organic matter to bacterial cells, carbon dioxide and water as described above. Cell recycling and wasting is required. It can be done by settling (Fig. 1) or by filtering. The units can be operated on a batch basis where wastewater enters a chamber, is held for a period and then discharged. They can be operated on a flow-through basis where influent enters the unit and equal amount of effluent exits. In both cases the flow is intermittent. Municipal units operate on a flow-through basis while individual home size units can be either batch or flow-through.
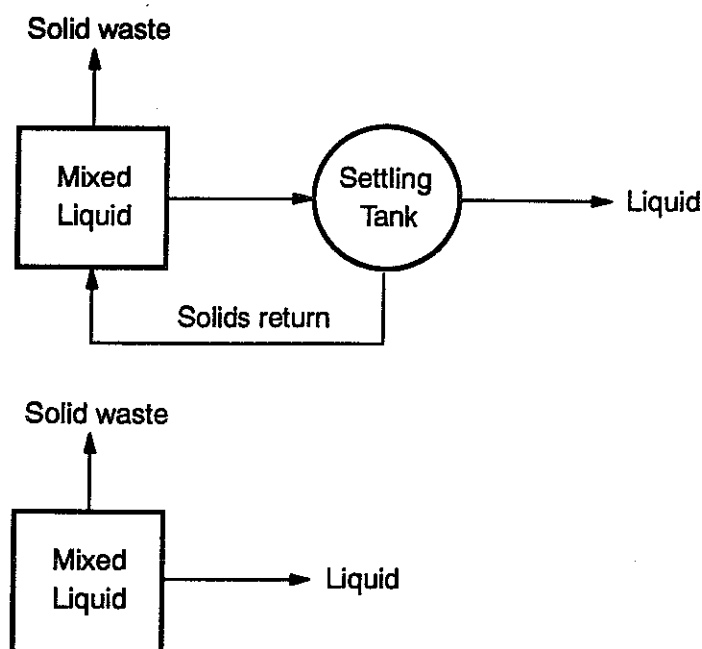
Fig 1. Schematics showing sludge wasting by settling and pumping (lower) and settling, recycling, settling and pumping (upper) (Modified from Metcalf and Eddy, 1991).

Such systems may be called activated sludge units (municipal) or aerobic units (individual). Systems may go through extended aeration where the wastewater is held longer and bacterial cells starve and are decomposed thus reducing the amount of sludge wasted for disposal. Home size units are normally designed to

operate in the extended aeration mode.

b. Fixed Film Systems

Trickling filters, rotating biological contactors and sand filters are fixed film or attached growth processes. The aggregate provides an attachment for the bacteria with the waste water passing over the bacteria. The bacteria removes the organic matter and nutrients from the wastewater. The process requires primary settling, such as a septic tank, prior to the effluent entering the filter. Suspended solids sloughing occurs in trickling filters and rotating biological contactors. Clogging of the sand, near the surface, may occur in sand filters, especially if they are heavily loaded with organic matter.

3. Microbial Growth

Figure 2 shows the typical microbial growth in a batch culture in which food is introduced and an inoculum is added. The growth and decline can be illustrated by four phases.

KEY: A Lag phase
      B Log growth phase
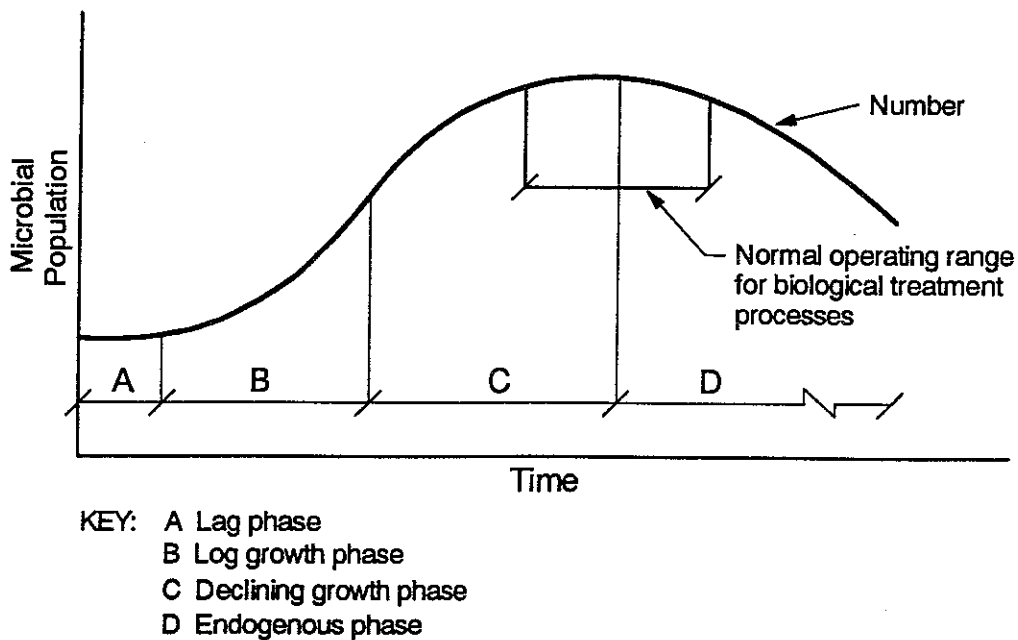   C Declining growth phase
      D Endogenous phase

Fig. 2. Microbial growth in batch culture (Henry and Heinke, 1989).

Lag phase (A):

The lag phase represents the time required for the organisms to acclimate to their environment and start to grow.

Log Growth Phase (B):

> Cells grow rapidly with the rate determined by their growth rate. Food is not the limiting factor.

Declining Growth Phase (C):

> Food starts to become limiting, slowing the growth rate. Bacterial cells start to die off thus decreasing the bacterial mass.

Endogenous Phase (D):

> Rate of death exceeds new cell production. Cells are forced to metabolize their own protoplasm as food is very limited.

In a continuous biological process, the system will operate as shown in Fig. 2 (Phase C and D). Individual home-size systems are more subject to shock loading as the rate of food supplied can vary considerably. For example, if no food (waste) is supplied for a long time (family on vacation) the activity shifts to the endogenous phase with a large reduction in bacteria. Once feeding resumes, the system will advance through the phases. Shock loadings can upset the system and take longer to get back into operation. The suspended growth systems are more prone to shock loadings than the fixed film units.

4. Nitrogen Transformations

Figure 3 shows the nitrogen transformation in biological treatment processes. Nitrogen is excreted in the form of organic nitrogen and ammonia. In the septic tank the organic nitrogen is converted to ammonium. In an aerobic environment the ammonium is converted to nitrite then to nitrate by bacteria. Typically aerobic conditions exist beneath soil absoprtion unit provided they are not overloaded or to large for oxygen too diffuse into the soil beneath the unit. Aerobic conditions exist in sand filters and aerobic units. Nitrates are denitrified if anaerobic conditions prevail and a food source is available for the denitrifiers. Economical and reliable nitrification/denitrification systems are being developed to reduce the risk of ground water pollution from nitrogen in effluent.
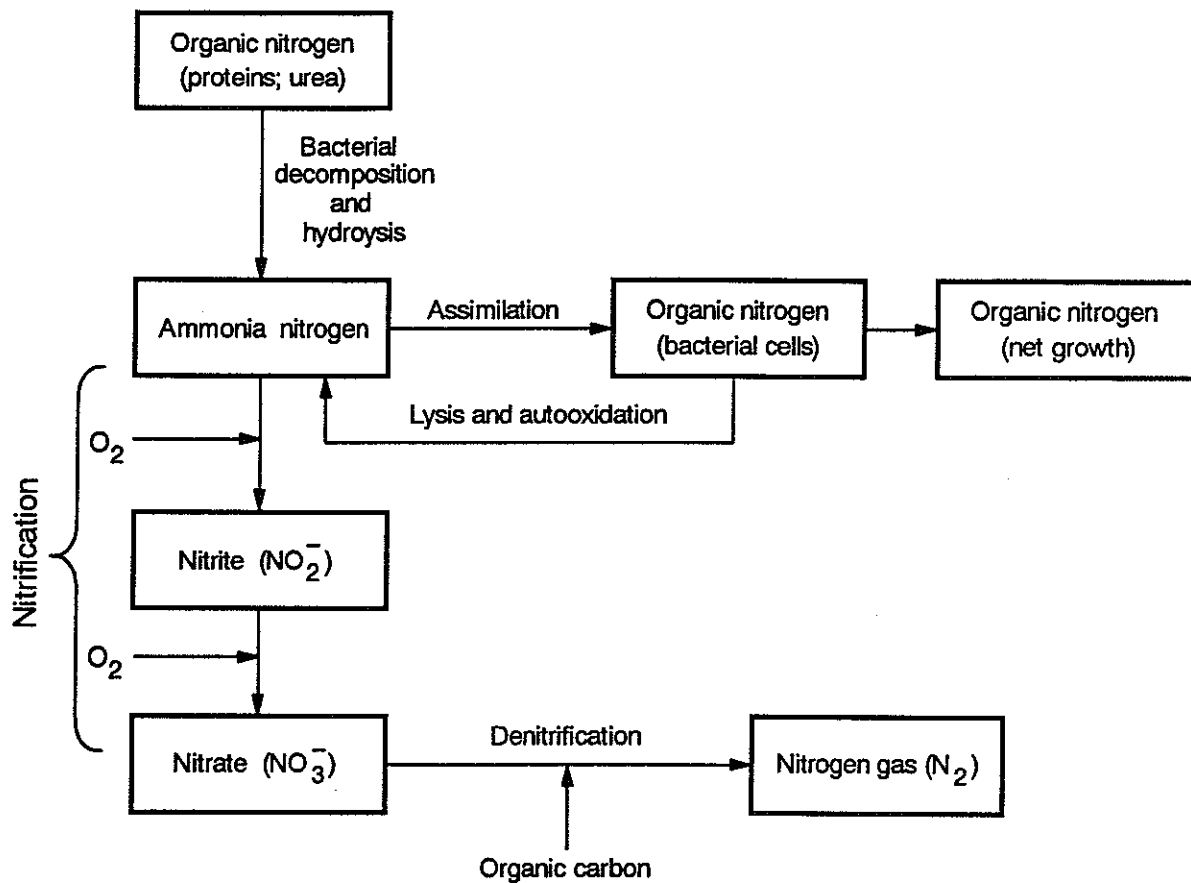
Fig. 3. Nitrogen transformation in biological processes (Metcalf and Eddy, 1991).

5. Biological Reaction Rates

Local environmental conditions, such as temperature, pH, and alkalinity, affect system performance. A temperature decrease of 18° F (10° C) will reduce the reaction rate by about one half.. Low-alkalinity wastewaters have little buffering capacity and the mixed-liquor pH may drop because of the production of carbon dioxide by bacterial respiration. Low pH values may inhibit the growth of nitrifying organisms and encourage the growth of nuisance filamentous organisms.

6. Effect of Temperature

Temperature affects the metabolic activities of the microbial population and also affects such factors as gas-transfer rates and settling characteristics of the biological solids. Reaction rates can be predicted by the following equation (Metcalf and Eddy, 1991).

$$r_T = r_{20} \, \theta^{(T-20)}$$

where: r_T = reaction rate at T°C
r_{20}= reaction rate at 20°C
θ = temperature-activity coefficient
Typical values are 1.04 for activated sludge and 1.035 for trickling filters.
T = temperature, °C

7. Buffering

Buffering is an important characteristic in wastewater. It offers resistance to changes in pH when an alkaline or acidic material is added or formed in the solution. Carbonates provide buffering capacity for acids and help to stabilize the pH.

8. Alkalinity

Alkalinity is a measure of the water's ability to neutralize acid and provides buffering against pH change. Wastewater with low alkalinity will not have the buffering capacity and pH can change quickly with the addition of an acid or CO_2 production through bacterial respiration. Total alkalinity is measured as mg/L as $CaCO_3$ and is the sum of the bicarbonate (HCO_3^-), carbonate (CO_3^{-2}) and hydroxide (OH^-) alkalinities.

9. Solids

Figure 4 shows the relationship of the various solids components associated with wastewater. One measure of system performance is reduction of suspended solids (SS).

10. Dissolved Oxygen Concentrations

Dissolved oxygen concentration is a function of temperature, salinity and barometric pressure. The following relationships exist:

As temperature increases, the saturated dissolved oxygen concentration (ppm or mg/L) decreases under constant pressure and salinity.

As the barometric pressure increases, the saturated dissolved oxygen concentration increases for constant temperature and salinity.

As the salinity increases, the saturated dissolved oxygen concentration decreases for constant temperature and pressure.
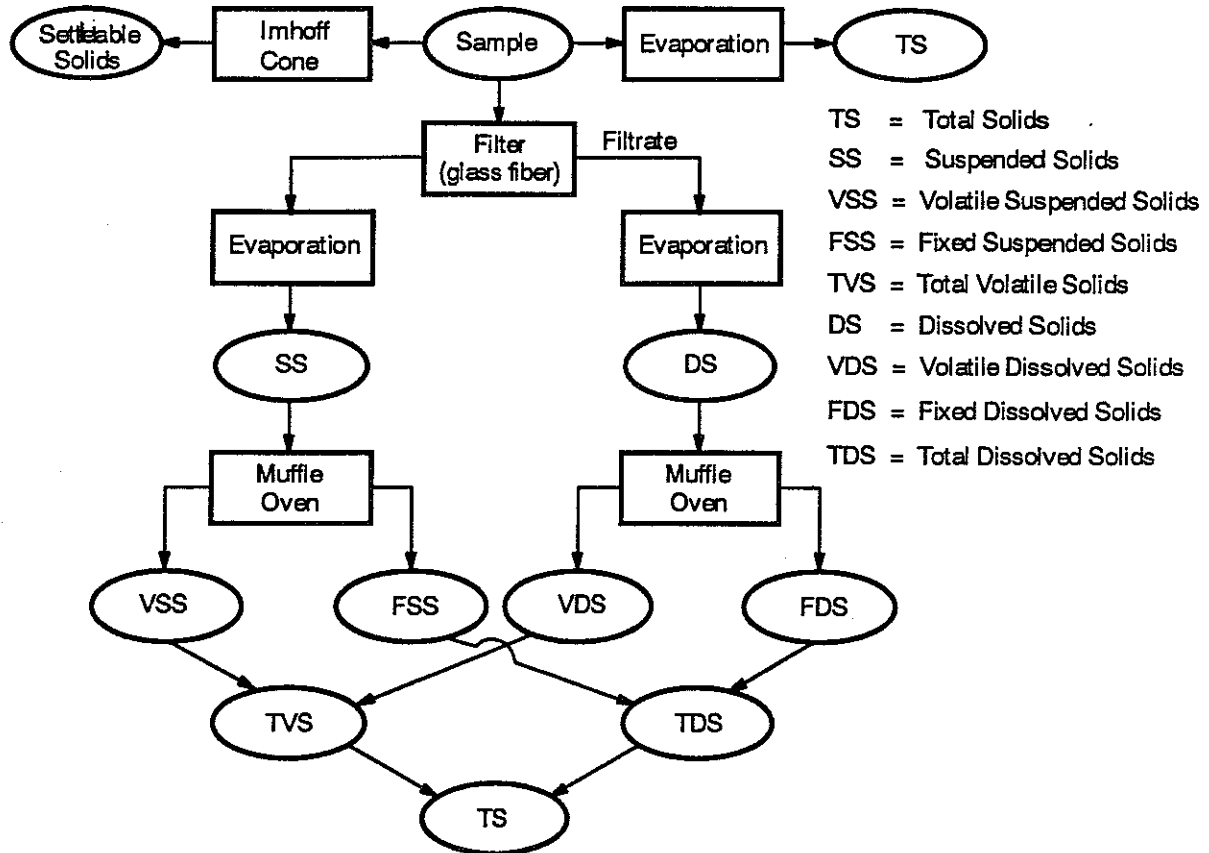
Fig. 4. Interrelationships of solids found in wastewaters. (Modified from Metcalf and Eddy, 1991).

At 20°C the saturated dissolved oxygen concentration varies from 8.77 to 9.32 for barometric pressures of 735-780 mm. For a barometric pressure of 760 mm, the D.O. ranges from 14.6 to 6.41 over the range of 0 to 40°C. Saturated dissolved oxygen typically range from 6-10 mg/L under our temperature, barometric pressure and salinity conditions.

11. Oxygen Transfer

Oxygen is transferred from the air into the water by diffusion. The rate of transfer is a function of 1) the surface of the interface between the air and the liquid, 2) the temperature and 3) the dissolved oxygen concentration/saturated concentration ratio for the temperature and pressure involved. The amount needed to maintain aerobic units is related to the oxygen demand (BOD). The rule of thumb for diffused-air aeration is 1.0 - 1.2 lb O_2/lb BOD_5 plus the oxygen required for nitrogen conversion of ammonia to nitrate.

a. Bubble diffusion:

In suspended media aeration, air is injected into the mixed liquor. As the bubbles rise to the surface, the oxygen is diffused into the liquid. Oxygen transfer efficiency is affected by the surface interface. For a given weight of air, smaller bubbles have much larger surface area than large bubbles and thus the transfer efficiency is much greater resulting in less energy input for a given amount of oxygen transferred.

b. Thin film diffusion:

In fixed media aeration where the effluent is dispersed over the surface of a media, such as sand, the effluent moves down through the media. The void area is filled with air where the oxygen diffuses into the thin films of liquid that pass through the voids. As the effluent moves downward, it draws air into the voids. Convection currents, due to temperature differences, also moves air into the voids. Oxygen diffuses due to a concentration gradient.

12. Typical Composition of Untreated Domestic Wastes

Table 1 gives the typical composition of domestic wastewater. These values will vary considerably and are only presented as a guide. In households that use low flow toilets and other water conservation devices, the concentrations will be greater. Restaurant wastes will normally be much stronger than these values.

13. Measurement of Organic Matter

Organic matter in wastewater is measured in several different ways. The most important is the BOD. Other measurements include COD and TOC.

a. Biochemical Oxygen Demand (BOD)

The BOD test is an indirect method of measuring the amount of biodegradable organic matter in the wastewater by measuring the amount of oxygen used by a growing microbial population to convert organic matter to carbon dioxide and water. The oxygen consumed (BOD) is proportional to the organic matter converted and therefore a relative measure of the biologically degradable organic matter present. Since biological oxidation continues indefinitely, the test for ultimate BOD has been limited to 20 days with about 95% of the oxygen demand

Table 1. Typical composition of untreated domestic wastewater (Metcalf and Eddy, 1991)

Contaminants	Unit	Concentration		
		Weak	Medium	Strong
Solids, total (TS)	mg/L	350	720	1200
Dissolved, total (TDS)	mg/L	250	500	850
Fixed	mg/L	145	300	525
Volatile	mg/L	105	200	325
Suspended solids (SS)	mg/L	100	220	350
Fixed	mg/L	20	55	75
Volatile	mg/L	80	165	275
Settleable solids	mL/L	5	10	20
Biochemical oxygen demand, mg/L: 5-day, 20°C (BOD$_5$, 20°C)	mg/L	110	220	400
Total Organic Carbon (TOC)	mg/L	80	160	290
Chemical oxygen demand (COD)	mg/L	250	500	1000
Nitrogen (total as N)	mg/L	20	40	85
Organic	mg/L	8	15	35
Free ammonia	mg/L	12	25	50
Nitrite	mg/L	0	0	0
Nitrate	mg/L	0	0	0
Phosphorus (total as P)	mg/L	4	8	15
Organic	mg/L	1	3	5
Inorganic	mg/L	3	5	10
Chloride[a]	mg/L	30	50	100
Sulfate[a]	mg/L	20	30	50
Alkalinity (as CaCO$_3$)	mg/L	50	100	200
Grease	mg/L	50	100	150
Total coliform	no/100 mL	10^6-10^7	10^7-10^8	10^8-10^9
Fecal Coliform	no/100 mL	--	10^5-10^6	--
Volatile organic compounds (VOCs)	μg/L	<100	100-400	>400

[a]Values should be increased by amount present in domestic water supply.

satisfied. A <u>5-day</u> BOD at 20°C is determined and used to calculate the ultimate BOD using the following equations (Henry and Heinke, 1989).

$$L = L_o(10^{-kt}) \quad \text{and} \quad L_o - L = L_o(1 - 10^{-kt})$$

where:

L = carbonaceous BOD remaining at time t
    (Oxygen needed to oxidize carbonaceous organic matter remaining).
L_o = ultimate carbonaceous oxygen demand (ultimate BOD)
    (Oxygen needed to oxidize carbonaceous organic matter initially present).
t = time (days)
k= rate constant (base 10) (day^{-1}) = 0.17 for domestic waste.

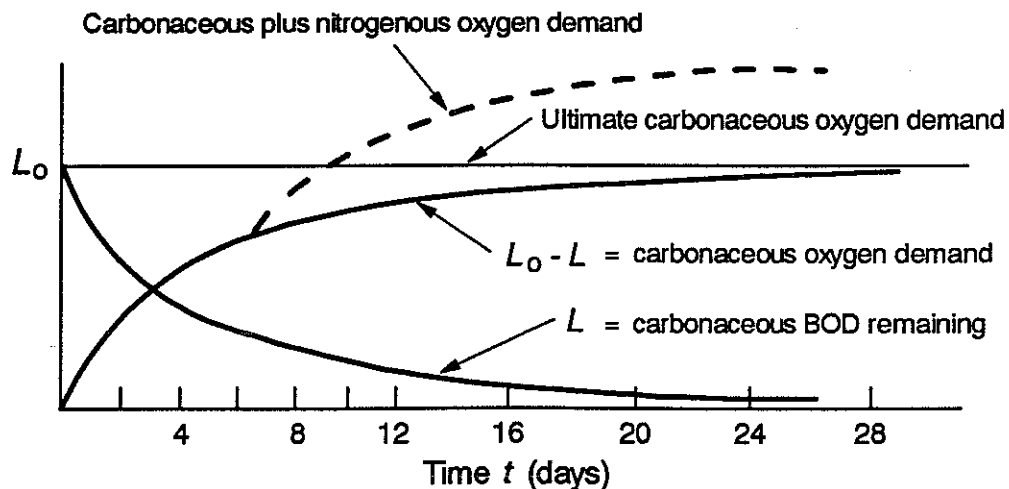Figure 5 represents a BOD curve at 20°C for the carbonaceous oxygen demand plus the nitrogenous oxygen demand.

Fig. 5. BOD curve at 20° C (Henry and Heinke, 1989)

b. Total Organic Carbon (TOC)

The total organic carbon is a measure of the amount of carbon which is combined in organic matter. It does not include carbon in carbonate, bicarbonate and carbon dioxide. It is determined by measuring the amount of carbon dioxide produced when the organic carbon in the sample is oxidized by a strong oxidizer and comparing it with the amount in a standard of known TOC. It is measured with a total organic carbon analyzer.

c. Chemical Oxygen Demand (COD)

The COD is the equivalent amount of oxygen needed to chemically oxidize the organics present in a wastewater using a strong oxidizing agent (usually hot, acid, dichromate solution).

14. Oxidation-Reduction (Redox) Reactions

(This section was prepared by James O. Peterson)

Chemical oxidation and reduction reactions are part of the aerobic and anaerobic processes. The chemical elements (oxygen (O), nitrogen (N), iron (Fe), sulfur (S) and carbon (C) etc.) may each have different oxidation states. The oxidation state is the result of the balance of electrons (negative charges, -) and protons (positive charges, +) in an atom of the element. When an atom has an equal number of protons and electrons, it is at its zero oxidation state (or valence). Nitrogen gas (N_2), oxygen gas (O_2), dissolved oxygen (molecular) , solid sulfur and iron metal are examples of the zero oxidation state.

Reactions

When elements react with each other, electrons are transferred from one element to another. For example, when hydrogen gas is burned in oxygen gas, the hydrogen is oxidized (loss of electrons) and the oxygen is reduced (gain of electrons) with energy (heat) released.

$$2H_2 + O_2 \ = \ 2(H \ - \ O \ - \ H)$$
$$(0) \ \ (0) \quad \ (+1) \quad (-2) \quad \ (+1) \quad \text{Oxidation state}$$
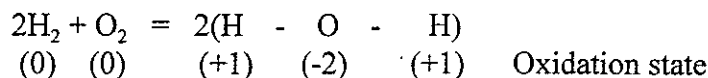
In this reaction, each oxygen gained two electrons and each hydrogen lost one electron with the net change being zero.

Some elements have several oxidation states that are stable under different conditions. Nitrogen may be in any of the following forms and as well as some others.

N (-3)	Ammonia (NH_3) and ammonium ion (NH_4^-)
N (0)	Nitrogen gas (N_2)
N (+2)	Nitric oxide (NO)
N (+3)	Nitrite ion (NO_2^-)
N (+4)	Nitrogen dioxide (NO_2)
N (+5)	Nitrate ion (NO_3^-)

Oxidizing Agents

An "oxidizing agent" is one that can accept electrons. For example, oxygen (O_2, molecular or free oxygen) is an oxidizing agent only in the zero oxidation state. It will not serve as an oxidizing agent (electron acceptor) in its combined or reduced state. Thus, we can not use oxygen from water or nitrate to breathe. We need the oxidizer form.

Oxygen is not required in all oxidation-reduction reactions. Chlorine or peroxide are strong oxidizing agents. Under specific conditions they are electrochemically eager to gain (accept) electrons in an oxidation-reduction reaction. (Tables are available describing relative strength of oxidizing and reducing agents.) At intermediate oxidation states, a substance may serve as an oxidizing or reducing agent. In the list of nitrogen forms above, nitrate may be an oxidizing agent or a reducing agent, depending upon the reaction conditions.

The following are examples of oxidation-reduction reactions.

Iron rusting - iron metal is oxidized and oxygen from the air is reduced.

Methane burning - carbon is oxidized and oxygen is reduced.

Hydrogen "burning" in chlorine gas - hydrogen is oxidized and chlorine is reduced.

Reaction Rates

Merely having the proper forms of elements and compounds together does not mean that a reaction will occur. The rate of the reaction may be dependent upon temperature, water, light and for on-site systems, microorganisms. For example, dry iron in dry air will not rust but if water is present, it will rust. A mixture of hydrogen gas and oxygen in a balloon is stable until an open flame is added and then it explodes. Bacteria convert nitrogen into various forms (ammonia, nitrite, nitrates and nitrogen gas) in aerobic and anaerobic treatment. The rate of reaction is sensitive to temperature, pH, dissolved oxygen, organic matter and other factors. For example, under aerobic conditions, nitrogen is oxidized (loses electrons) to nitrite and then to nitrate. Under anaerobic conditions, the nitrate is reduced (gains electrons) to nitrogen gas with the oxygen cleaved off. In both cases, specialized bacteria are required.

REFERENCES

Henry, J. G. and G.W. Heinke, 1989. Environmental Science and Engineering. Prentice Hall, Englewood Cliffs, NJ. 07632.

Metcalf and Eddy. 1991. Wastewater Engineering. McGraw-Hill Inc. New York.