

Anaerobic Processes (Chapter 10)

Used for treatment of sludges and high strength (usually > 1500 mg/L COD) waste waters
Can now be used for dilute strength waste waters if a fixed film system is used
90% of new treatment processes in developing countries (i.e. Mexico) are anaerobic.

Advantages

1. Less energy required (no aeration needed)
2. Produces less sludge to be disposed of
3. Fewer nutrients required
4. Smaller reactor volume required
5. Produces energy in the form of CH₄ which can be used to fuel plant
6. Reduces pathogens in the sludge
7. Low operating costs
8. Rapid response to substrate addition after long periods without feeding.

Theory

Anaerobic conditions, i.e. no oxygen.

Available electron acceptors for anaerobic respiration include nitrate, sulfate and CO₂.

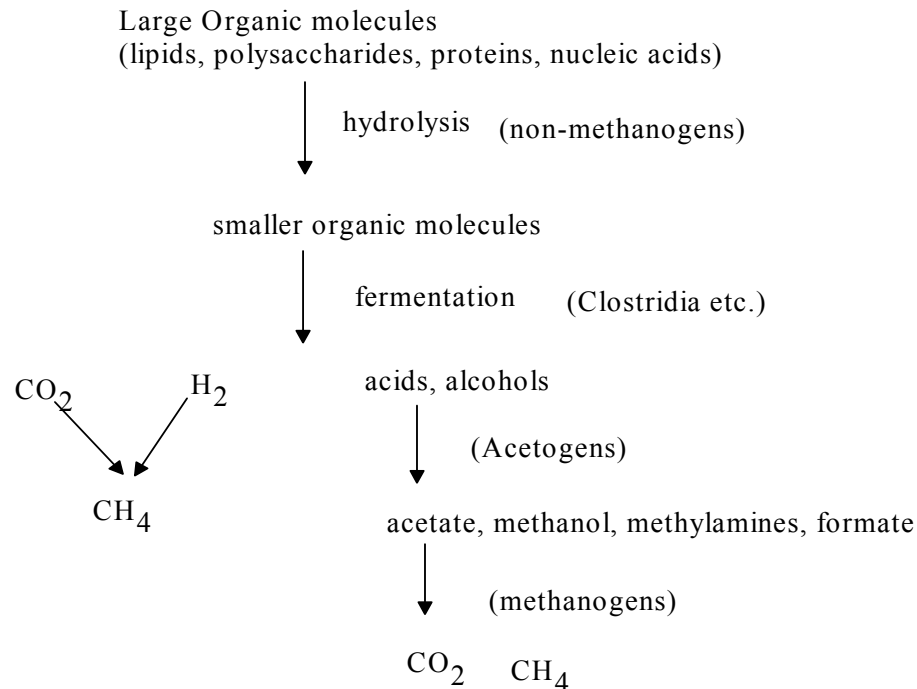
I haven't seen any references to iron or other metal reduction as an industrial treatment process.

Depending on the presence of the alternative electron acceptors different processes occur.

1. If nitrate is present it will be used first, the most energy is maintained for the cell and more organisms can do this.
2. If sulfate is present it will be used after the nitrate, this is usually not desired so sulfate input is usually guarded against, some always gets in so there have been methods developed to remove sulfide from the gasses produced and also control methods for precipitating sulfide into the sludge. (If an anaerobic reactor goes bad add some iron. It usually helps)
3. Methane production. Methanogenic organisms do not degrade large organic molecules, they can only use H₂ and one carbon compounds such as methanol, acetate can be used by some species, and these tend to dominate the population in municipal sewage sludge digestors (along with the hydrogen/CO₂ utilizing methanogens.

Methanogens only grow in very reduced conditions (-250 mV) and they grow rather slowly. Because of these requirements a mixed population of organisms is always required for methanogenic systems growing on large organic molecules.

Methanogenic process overview



The procedure requires the complete cooperation of all of the organisms because if the non-methanogens didn't produce the acetate and hydrogen then the methanogens couldn't exist, conversely if the methanogens didn't remove the H₂ (interspecies hydrogen transfer) and acetate then the fermentations would be limited by the concentrations of the products. Therefore a consortium is needed.

The process is usually run at 30 -38°C or at 49-57°C (thermophilic) the organisms at the different temperature are different. Laboratory incubations are usually performed at 37°C or 55°C.

Oxygen removal

For sludge digestion there is usually no need for any specific attempt at oxygen removal. The BOD in the sludge ensures any oxygen is scrubbed out rapidly. Sealing the unit prevents new diffusion of oxygen.

For lab studies and for some industrial wastes oxygen removal must be performed, heating the water and cooling in an atmosphere of N₂ gas works.

In some circumstances an additional carbon source is added and the waste is put through a precolumn in which the aerobes scrub out the oxygen before the waste is actually put through the methanogenic column

A practical solution is twin the waste stream with a municipal sludge stream.

Gas phase

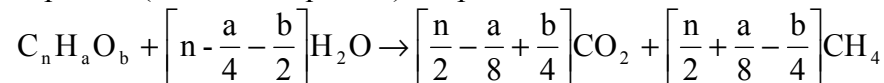
The production of CO₂ and Methane during a methanogenic process usually results in a head space gas of about 30% CO₂, 70% CH₄ and small amounts of N₂, H₂S etc. The methanogens actually require elevated amounts of CO₂ due to their dependence on it as an electron acceptor and carbon source.

The elevated CO₂ in the atmosphere increases the amount of dissolved CO₂ and subsequently decreases the pH. Methanogens must have a pH of above 6.2 so a decrease in pH is not good. This is controlled by keeping a balancing concentration of bicarbonate (alkali) to buffer the CO₂.

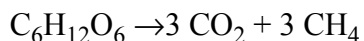
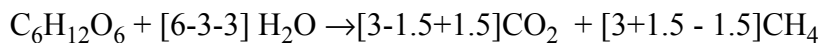
The gas can be recovered, the CO₂ scrubbed out and the methane used as fuel.

Gas Calculations

Using single compound (Buswell's equation) simplified from the one in the text.



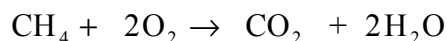
e.g. glucose (C₆H₁₂O₆)



therefore will produce 3 mol of methane for every mol of glucose.

Calculation per BOD

Once you get the amount of methane per mol of glucose you determine what the ultimate BOD would have been if it hadn't gone to methane. i.e.



In the case of glucose you produced 3 methane so you will need 6 O₂ to convert it all to CO₂.

since the only oxygen required was to oxidize the methane to CO₂ the demand of O₂ in g is 6

mol x 32 g/mol = 192 g for 1 mol of glucose (180 g)

the weight of CH₄ produced is 3 mol x 16 g/mol = 48 g methane produced per mol glucose (180 g)

therefore a ratio can be calculated for the wt of methane per weight of BOD_U

$$\frac{48/180}{192/180} = 0.25$$

and it can be seen that each g of BOD will produce 0.25 g of methane.

to determine the volume of this you can use the fact that 22.4 L of gas equals 1 mol of gas at STP (25.29 at 35°C).

Since we were producing 3 mol of methane per mol of glucose that would be 67.2 L for each mol of glucose. To convert this to a BOD_U basis.

$$V = \left(\frac{0.25 \text{ g CH}_4}{\text{g glucose}} \right) \left(\frac{1 \text{ mol CH}_4}{16 \text{ g CH}_4} \right) \left(\frac{22.4 \text{ L}}{\text{mol}} \right) \left(\frac{\text{ft}^3}{28.32 \text{ L}} \right)$$

$$= 0.012 \text{ ft}^3 \text{ methane per g BOD}_U$$

$$\text{or } 0.012 \times 454 = 5.62 \text{ ft}^3 \text{ methane per lb BOD}_U$$

This is done because very often the analysis is not mol of glucose but lb of BOD_U.

Calculation per COD

The COD of one mole of CH₄ is equal to 64 g, the amount of CH₄ produced per unit COD is 0.4 L CH₄/ g COD.

Mass balance for calculation of methane production

$$V_{\text{CH}_4} = 5.62[(S_o - S)(Q)(8.34) - 1.42 P_x]$$

5.62 = conversion factor we calculated above

S and S_o are in ultimate BOD terms

P_x is in lb/d

$$P_x = \frac{Y[(S_o - S)(Q)(8.34)]}{1 + k_d SRT} \text{ US units}$$

Or in SI units

$$V_{\text{CH}_4} = 0.35 [(S_o - S)(Q)(10^3 \text{ g/kg}) - 1.42 P_x]$$

$$P_x = \frac{Y[(S_o - S)(Q)(10^3 \text{ g/kg})]}{1 + k_d SRT}$$

Types of Anaerobic Processes

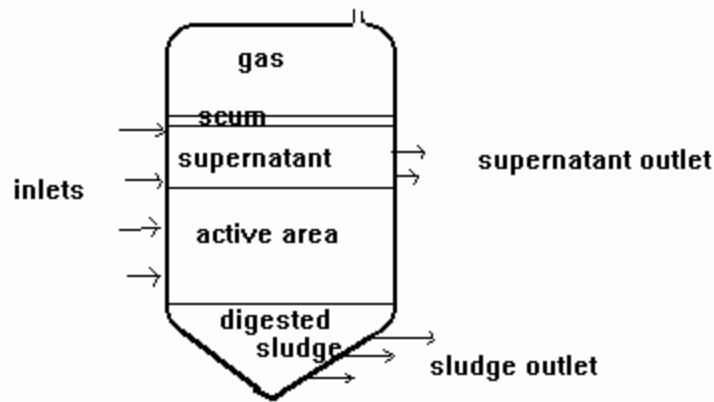
1. Anaerobic digestion (This is from Chapter 14-9)

Biosolids and primary sludge digestion

suspended growth system

two types

a) Standard (non-mixed)



30-60 day detention time
can be run continuous or semi-continuous

- b) High Rate (complete mix- thermophillic)
15 d detention time
usually needs a settling tank.

Performance Characteristics

Effects of Temp, SRT, pH on performance (Overheads- next 4 pages just for examples not in text)

Performance measured by gas production or VS removal

as temp increases up to 35°C methane production and VSS removal go up, units are ft³/lb, therefore the increase is not just in rate but in amount of gas produced/per substrate, thus we are getting less fermentation and more methanogenesis

for thermophilic reactor use temps up to 65°C

SRT of at least 10 days is required at 35°C to get maximal reduction in effluent COD and methane production

SRT needed to get maximal VS reduction gets longer when temp. decreases.

Optimal pH is between 6.8 and 7. Cells very pH sensitive.

Design of Anaerobic Digestors

The design should be based on the microbiology and biochemistry of the system. Anaerobic systems are not as forgiving as activated sludge systems so should be tested in lab systems and pilots before large scale operations are built.

Sizing digestors

- 1) solids retention time as a basis for sizing reactors
- 2) volumetric loading factors
- 3) volatile solids destruction (read text)
- 3) observed volume reduction (read text)
- 4) loading based on population (read text)

Mean cell residence time

Since in complete mix digestors the hydraulic detention time = the SRT the SRT can be used to size reactors. There is no recycle since we are treating cells. Suggested mean cell residence times for complete mix digestors are: table 14-26

Operating temp °C	SRT minimum (d)	SRT suggested (d)
18	11	28
24	8	20
30	6	14
35	4	10
40	4	10

Example in text 14-5

2. Loading Factors

Use a loading factor to determine the required volume

a) lb of VS per day per ft³

b) lb of VS per day per lb of VS in the digester

similar to food to microorganism ratio Table 14-27 in text (overhead)

Pictures of different digestors next few pages.

2. Anaerobic Suspended growth Treatment processes (Back to Chapter 10)

Suspended growth processes are designed similarly to aerobic processes. Table 10-9 (overhead) summarizes the design procedure Table 10 10 summarizes design parameters. An example design is in example 10-2 (overhead).

The anaerobes get much less energy for degrading the compounds so grow very slowly. Thus we usually use technologies to help keep the sludge in the reactors. The development of these technologies has revolutionized high strength wastewater treatment.

The most widely used suspended growth process is the upflow anaerobic sludge blanket (UASB) reactor. Two new similar types of reactor are the anaerobic baffled reactor and the anaerobic migrating blanket reactor.

Anaerobic Upflow Sludge Blanket Reactor

Anaerobic growth forms a granular floc (1 to 3 mm). These granules are kept in suspension in an upflow reactor. The waste enters the reactor and flows up through the sludge blanket. (Figure 10-4 overhead)

The gasses produced provide mixing, and also cause some of the biomass to rise, the biomass hits baffles, release the gas and falls back down to the sludge blanket

There are several designs for reactor configuration.

Keeping a well granulated floc is of the utmost importance to a UASB process.

The most important factors in floc granulation are

- near neutral pH
- plug flow hydraulic regime
- zone of high hydrogen partial pressure
- nonlimiting supply of NH_4
- limited amount of the amino acid cysteine

The important design considerations are

1. wastewater characteristics
2. volumetric organic load
3. upflow velocity
4. reactor volume
5. influent distribution system
6. gas collection system

Table 10-11-10-13 (overheads) presents some recommended loading factors for UASB design. Your text explains the terms. Example 10-3 presents an example design (overhead)

Attached Growth Reactors

- good for strong or dilute wastes
- columns containing packing material (usually activated carbon, although others have been reported.
- usually run as upflow rather than downflow, easier to control.

Types

- a). Packed Bed - column completely filled with activated carbon or other media
- cells bind to media so you can have long detention times
 - organics bind to carbon, this concentrates them in the area of the bacteria
 - can have very fast hydraulic rates and still have the cell detention necessary for slow growing anaerobes
- problems - column can plug eventually, no easy way to get cell sloughing away from the media have to remove some media.
Table 10-18 (overhead) has some examples.

- b) Expanded bed - column not packed tight (usually use sand or activated carbon)
- flow adjusted so that the media is suspended in the flow
 - very high biomass concentrations can be obtained
 - very short hydraulic detention times also
 - has been demonstrated effective for municipal wastes as long as sulfate is kept under control
- Table 10-19 has example performances.

- c). Fluidized bed - column not packed full
- very high flow rates actually fluidize the packing material
 - biomass that is sloughed off is flushed to the top and collected

- get a good mixing from the fluidization, the packing material changes weight as the biomass grows and is sloughed off so it is constantly cycling up and down.
 - has been used to treat contaminated soils, gasses, and waste waters from industrial sources
- Table 10-21 has examples (overhead)

Sludge Disposal And Treatment (Chapter 14)

Types of Sludges

Screenings - rocks, branches, rags, roots, paper, leaves etc.

Grit - sand, gravel, cinders, dense solids, smaller particles.

Scum - grease, hair, oils, vegetable skins, fats, soaps, etc.

Primary Sludge - suspended solids that settle out in primary settler, Usually very smelly, and slimy. Table 12-4 lists some properties of primary sludge before and after digestion.

Chemical Precipitation sludge - metal salts, has odor, is slimy.

Biological solids - waste activated sludge, trickling filter sludge, anaerobic sludge

Quantities

Table 14-7 lists some qualities and quantities of sludge that can be produced from various processes in wastewater treatment. Of course, the type of wastewater and the flow rate will have a definite effect on the quantities of sludge that are produced. The data given as dry solids is misleading because most sludges are less than 10% solids. Table 14-8 presents the solids content as a %. There is still a lot of water present in these sludges.

Treatment (Figure 14-2 – 14.3. Sludge treatment flow diagrams)

Sludges must be treated before disposal. They can be treated to two different standards

1. Class A - safe for use by general public as amendments in for use in gardens greenhouses nurseries etc. Fecal coliform density less than 1000 MPN/g dry solids or *Salmonella* less than 3 MPN/4 g dry solids
2. Class B – typically not treated as well and used for agricultural land or disposed of in a landfill.

Table 14-9 presents methods to reduce the pathogens in sludge

Table 14-10 presents ways to reduce vector attraction. (Vector attraction is a nice word for putrefaction of solids, which would attract flies etc.)

Pretreatment

(these are used to make the sludge easier to treat)

Grinding - grinder destroyed large particles to help prevent clogging of pipes and wrapping of sludge

Degritting - centrifugal forces remove grit from sludge.

Blending - to produce a uniform mixture for treatment

Storage - smoothes out fluctuations in sludge supply.

Thickening (primary and biological sludges)

increases solids content by decreasing water content.

Methods

- gravity - round tank, slow gentle stir to allow water out, sludge settles to bottom, (up to 6% concentration). Table 14-19 (overhead) has some loading factors.
- dissolved air flotation - pressurize the solution, introduce air, depressurize. The air bubbles carry the sludge to the top where it is removed. Used most with activated sludge and in Europe, (up to 5% concentration) Table 14-20 has some loading factors (overhead).
- centrifuges - Bowl - spin the sludge to the side where a screw device moves it to a cone and they are removed. The water moves up the middle. (up to 6% concentration)
 - Basket - batches of sludge are introduced into a spinning bowl, the water goes through the bowl, when the batch is done, (60 to 85% of side depth) the sides are scraped after the bowl is slowed down. (up to 10% concentration)
- gravity belt - Belt moves over rollers, polymer is added to sludge and then the mix is distributed over the belt, the water drains through the belt, the sludge is ridged and furrowed to allow the water access to the bottom. (up to 6% concentration)
- rotary drum - rotating screen drums, sludge with polymer added to it is put in drum, the drum rolls the sludge is retained inside by the screen and the water drains through. Sludge eventually rotates out the other end. (up to 9% concentration)

Stabilization (primary and biological sludges)

reduce odors, pathogens, putrefaction Technique used depends on the ultimate disposal plans.

1. Alkaline Stabilization

2. Anaerobic Digestion
3. Aerobic Digestion
4. Composting

Table 14-23 and 14-24 (overheads) summarize these processes.

1. Alkaline Stabilization

Lime is added to raise the pH of the final dewatered solids to > 11 . If the pH is maintained above this level for at least 24 hours, then the sludge is stabilized and can be used for land disposal. The pH will eventually reduce to neutral due to the reactions discussed in section 14-8.

2. Anaerobic Digestion – discussed this already.

3. Aerobic digestion. Typical of other aerobic processes but longer detention times allow higher input of BOD. Requires lots of O_2 but stream is smaller. $10 - 20 \text{ d } \theta$, 40-50% reduction in VSS. Book describes well. I think it is a waste of O_2

4. Composting - this is also a disposal method, since the material is not a sludge when it is done. This method is cost effective, and growing in use currently due to the fact that when metals are controlled the composted sludge can be sold as a soil amendment or if composted very well as a potting soil.

Composting process

Solid phase microbial digestion

Biosolids mixed with bulking agent (wood chips, shredded paper) and placed in piles or windrows. The piles are turned or aerated in some manner to allow sufficient O_2 .

Concentrated organics in solid phase provide a substrate at such a rate that the bacteria degrade the compounds so fast they actually start to heat the pile.

The heat produced causes faster reaction rates so the process goes quicker, Air must be added at such a rate that the pile does not overheat and kill off the organisms, (around 55°C).

The heat acts like pasteurization and kills off the nuisance organisms or pathogens.

The end product is sanitary, nuisance free, humus like material. Depending on how long you treat it and on how you age it it can be used as a soil conditioner or potting soil.

Must be careful of regulated pollutants (overhead).

Aerobic composting is most common, reactions happen very quickly so it is hard to keep good O_2 supply. If anaerobic pockets develop get odors.

Microbiology

Bacteria - mesophilic at first, then thermophilic and then mesophilic again

Fungi - same as above

Actinomycetes - branched chain bacteria, make dirt odor.

Table 14-39 presents the destruction of pathogens

Problems

Sludge is high in moisture, low in porosity, so good O_2 transfer is hard to get unless you add a good bulking agent. Wood chips best, but new process adds Styrofoam as recyclable bulking agent. Austin uses tree clippings, others are straw (or other waste

from agricultural products). Usually are used to supply void spaces for proper aeration but also serve as a source of increased degradable organics. For sludges you don't really need degradable organics, for some other uses of composting you need more organics. Table 14-38 (overhead).

Aeration

supplies O₂

cools the pile to keep it in the right range.

Optimal conditions

Max. temp	70°C best activity at 52 - 63°C
Moisture	50 - 60% water must be present
C:N	not > 40-1 not < 25-1
pH	6-9

Processes

1. Windrow - long row of material in 3-6 ft high 6 to 14 ft base pile, is turned every so often with large machine. (Figure 14-35 b and c)
2. Aerated Static Pile - 7-8 ft high pile put on a grid of piping, air is either pumped or suctioned through the pile. (Figure 14-35 a)

Both of these usually have a 21-28 d incubation. The solids are then screened to remove excess bulking agent and then cured for 30 days

3. Composting reactors (In vessel) - Many types and styles of biological solid phase reactors. These promise much faster reaction times, since they can promise much better mixing and temperature control. The reactor starts at a high temperature rather than gradually building up the temperature. These reactors minimize odors, land costs and time. (Figure 14-36 and 14-37)
3 categories a) plug flow - first in reactor first out of the reactor, usually put compost in the top of the reactors and it comes out the bottom, the air goes in the bottom and out the top.
b) dynamic - mechanical mixing and aeration keep the new mixed with the old.
c) batch - more for treatment of contaminated soils, use air for mixing and temp control as well as aeration. Same principle as always just no flow through.

Parameters that must be known (Design considerations Table 14-37)

total volume
wet weight
dry weight (solids content) and %
volatile solids content
water content
bulk density

The dewatering system is very important.

Can be mixed with MSW as the bulking agent, then it might not need dewatering.

4. Heat Stabilization - use of heat to disinfect

continuous process in which sludge is heated in a pressure vessel up to 500°F at pressures up to 2760 kN/m² for short periods of time (30 min). Is essentially the same as the heat conditioning process.

Conditioning

1. Chemical - makes the sludge easier to dewater.

add polymer - it coagulates the solids particles and releases the absorbed water
(Table 14-40 Polymer addition).

2. Heat - Heat for short period of time as discussed above. High cost.

Dewatering

Vacuum filter - vacuum applied downstream of filter media forces the water through.

Solid Bowl Centrifuge - same principle as discussed for thickening

Basket centrifuge - “

Belt Filter press - conditioned sludge is pressed between two belts to allow the water to be squeezed out.

Recessed Plate filter press - batch process where pressure is used to push water through filter plates that retain solids

Drying Bed - the solids are pored over a sand bed. The water either evaporates or drains down through the sand.

Lagoons - solids are spread into lagoon and allowed to dry

Land Application (Section 14-17)

The solids are applied to land as a soil amendment or fertilizer or are injected into or sprinkled onto land that is not being used for agriculture, strictly as a disposal method.

There are certain parameters that must be met before this can be done.

must reduce pathogens and organic content

must meet loading limits for pollutants, (nitrate, metals, organic)

annual and/or cumulative limits must be met

will also have a maximum limit for metals etc. that will dictate the life of your site.

Will have to obey nutrient loading. p. 1614 different calculations for each nutrient

Nitrogen - most N in sludge is organic, so must take into account mineralization and release as well as NH₄⁺ or NO₃⁻.

$$L_N = [(NO_3) + k_D(NH_4) + f(N_o)]F$$

Where

L_N = plant available nitrogen in the application year (g N/Kg biosolids)

NO_3 = % nitrate nitrogen in the biosolids, (decimal)

K_D = volatilization factor for ammonia loss

= 0.5 for surface applied liquid sludge

= 0.75 for surface applied dewatered sludge

= 1 for injected liquid or dewatered sludge

NH_4 = percent ammonia nitrogen in sludge, decimal

F_N = mineralization factor for organic nitrogen

= 0.5 for warm climates and digested sludge

= 0.4 for cold climates and digested sludge

= 0.3 for cold climates or composted sludge

N_o = percent organic nitrogen in sludge, decimal

F = conversion factor, (1000 g/Kg of dry solids)

The actual loading rate is then calculated by the following

$$L_{SN} = U/L_N \quad (\text{Kg/ha yr})$$

where U = the crop uptake of nitrogen (Kg/ha yr)

$$\text{Phosphorous } R_p = U_p / C_p (2000)$$

R_p = phosphorous limited sludge application (Kg/acre yr.)

U_p = Crop uptake (Kg/ha yr.)

C_p = % P in sludge

For individual pollutants

$$L_S = L_C / CF$$

L_S = max. biosolids that can be applied per year (Mg/ha yr)

L_C = max. amount of pollutant that can be applied per year (Kg/ha yr)

C = pollutant concentration in biosolids (mg/Kg)

F = conversion factor, (0.001 Kg/Mg)

Land requirement

Once you determine the rate of application calculations, you pick the limiting rate and use this to determine how much land you need for the amount of sludge you produce.

$$A = B/L_S$$

A = land area (ha)

B = sludge production rate (Mg/ yr)

L_S = limiting rate of application (Mg/ha yr)

There is also a cumulative limited lifetime application for several contaminants (especially metals). Examples in book very straight forward.