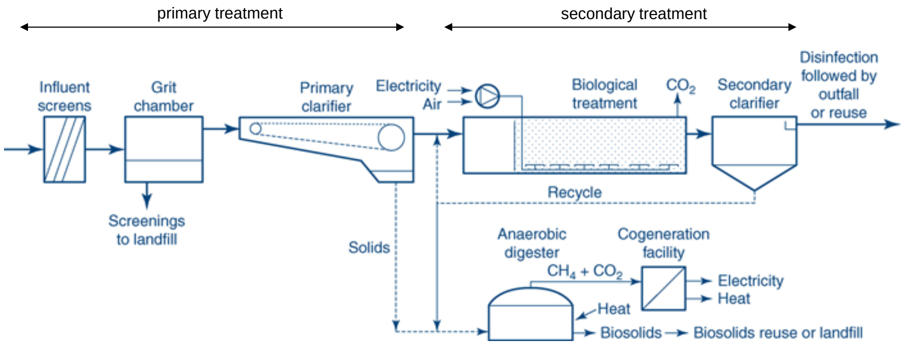
Biological Wastewater Treatment – Part 1

(Nazaroff & Alvarez-Cohen, Section 6.E – augmented)

Aerial View of the Water Reclamation Plant in Hanover, NH

(http://www.hanovernh.org/Pages/HanoverNH_PublicWorks/WaterRecl/Index)

Wastewater Treatment Plant (WWTP) – System Overview



Primary treatment = PHYSICAL
Secondary treatment = BIOLOGICAL

(Mihelcic & Zimmerman, Figure 11.4)
(See also Nazaroff & Alvarez-Cohen, Figure 6.B.2)

Primary treatment: Physical removal

Example of bar screen
as first step in primary treatment

http://photos.innersource.com/

filtered water

Example of grit chamber
as second step in primary treatment

http://www.vsfcd.com/primary.htm

water

grit to landfill

Example of
primary clarifier
as third step
in primary treatment

www.takamotobiogas.com/tag/missoula/

floating grease to incineration or disposal

bottom sludge to anaerobic treatment

water to secondary treatment

Secondary Treatment: Activated Sludge

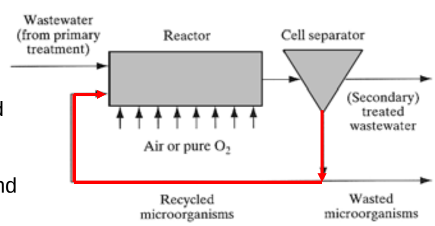
(Nazaroff & Alvarez-Cohen, Section 6.E.1)

An activated-sludge reactor is a system in which pre-treated sewage (*i.e.* having passed through primary treatment) is aerated to promote the growth of bacteria (cells) that gradually consume the organics in the sewage.

The result is the development of cells acclimated to the particular mix of substances present in the sewage and a significant consumption of the organic material. The effluent is a mixture of water with suspended cells and drastically reduced BOD content.

This mixture is then passed through a clarifier (settling tank) where the solids (mostly cells, called sludge at this stage) are separated from the water. The system is commonly operated in continuous mode (as opposed to batch mode).

The system is properly speaking an *activated-sludge* system when a portion of the sludge (cells) collected from the bottom of the clarifier is returned to the aerator. Not only are these cells already acclimated to the sewage, but by the time they are collected from the clarifier, they are also starved and really "hungry" for another meal!



(Nazaroff & Alvarez-Cohen, Figure 6.E.1)

Alternative 1: <u>Trickling Filter</u>

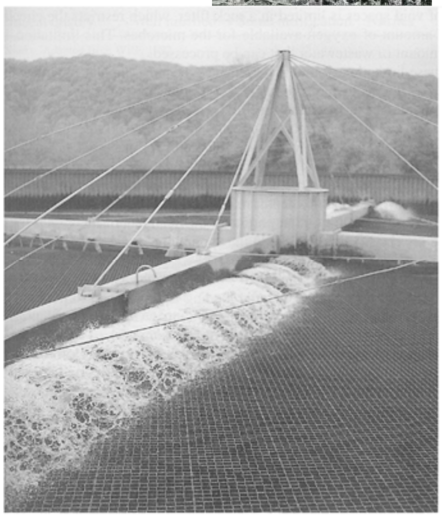
A trickling filter consists of a substrate (rocks or other material) on which cells can grow and over which the pre-treated sewage is sprayed. The spraying action creates contact between BOD in sewage, oxygen in the air and cells on the substrate. Cells grow and degrade the sewage. Excess cells (slime) need to be periodically removed from the substrate.

en.wikivisual.com

http://www.thecityofportland.net/wastewater

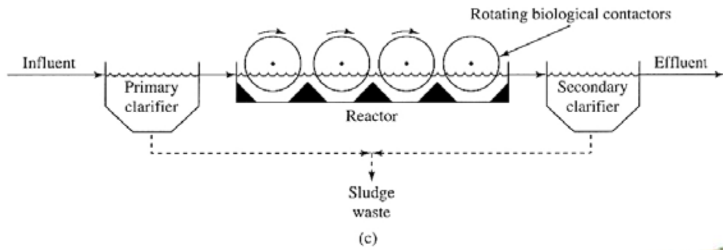
A trickling filter in action at the wastewater treatment plant in Portland, Indiana.

www.training.gpa.unep.org



Trickling filters: over rocks (left) and over synthetic media (right) (From Davis & Cornwell, 2008)

Alternative 2: <u>Rotating Biological Contactors</u>



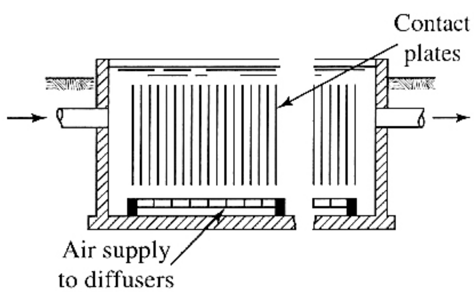
Sincero & Sincero, 1996

In this process, cells are attached to disks that rotate in the vertical plane. Cells are then alternatively exposed to sewage (their food) and air (their oxygen supply).

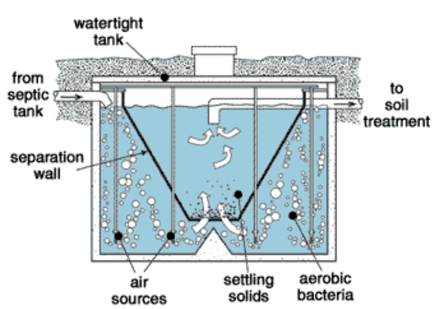
www.mayglothlingwaste.co.uk/treat_plant.php

Alternative 3: <u>Fixed-film Reactors</u>

In this process, cells are attached to vertical plates that are immersed by the flowing sewage and air is injected from the bottom to provide the oxygen.

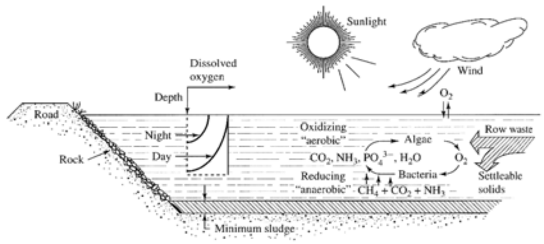


Sincero & Sincero, 1996



www.extension.umn.edu/distribution/naturalresources/

Alternative 4: Aerated Lagoons and Stabilization Ponds



http://www.lagoonsonline.com/technote5.htm

In this process, nature is essentially left to run its course, with or without a little help from aeration.

The system looks less technological and is thus better integrated in the landscape, but it occupies much more real estate. Odor may also be a nuisance.

http://www.lagoonsonline.com

Alternative 5: Eco-machine (John Todd Ecological Design)

www.toddecological.com/

inside

Rest area and welcome center along Interstate 89 in Sharon, Vermont.

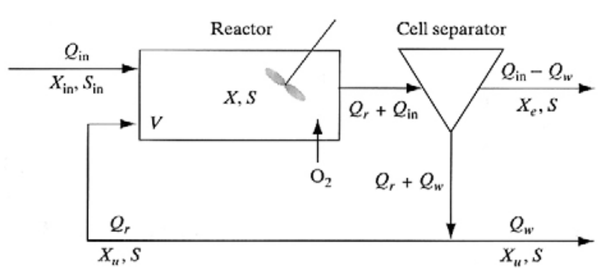
The wastewater from the toilets is treated on site by an eco-machine designed by John Todd.

Comparative summary of biological wastewater treatment technologies

Technology	Applications	Advantages	Disadvantages
Activated sludge	Low concentration organics Some inorganics	Removal of dissolved constituents Low maintenance Destruction process Relatively safe Low capital costs Relatively easy to operate	Volatile emissions Waste sludge disposal High energy costs Susceptible to shock and toxins Susceptible to seasonal changes
Trickling filters, Fixed-film reactors	Low concentration organics Some inorganics	Removal of dissolved constituents Low maintenance Destruction process Relatively safe Reduced sludge generation	Volatile emissions Susceptible to shocks and toxins Susceptible to seasonal changes Relatively high capital costs Relatively high operating costs
Aerated lagoons, Stabilization ponds	Low concentration organics Some inorganics	Removal of dissolved constituents Low maintenance Destruction process Relatively safe Low capital costs Low energy costs Easy to operate Infrequent waste sludge	Volatile emissions Susceptible to shocks and toxins Susceptible to seasonal changes High land requirement No operational control
Anaerobic degradation (septic systems)	Low concentration organics Chlorinated organics Inorganics	Removal of dissolved constituents Destruction process Treatment of chlorinated wastes Methane generation (= fuel) Reduced sludge generation	Susceptible to shocks and toxins Susceptible to seasonal changes Relatively high capital costs Relatively high operating costs

Activated-sludge system

The activated sludge system consists of two components, an aerator, where cells (*X*) consume the sewage (*S*), and a clarifier, where cells are then removed from the treated water.



(Nazaroff & Alvarez-Cohen, Figure 6.E.2)

Because cells need oxygen for their metabolism, air is injected from the bottom of the aerator. Rising bubbles agitate the water well and create good contact between the three ingredients: cells, sewage and oxygen.

Activated-sludge aerators are well agitated by mechanical stirring from the top or injection of air from the bottom.

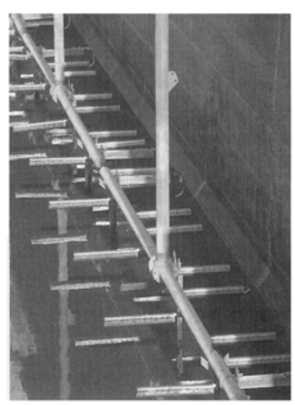
An *activated sludge* reactor with surface mechanical aeration / oxygen supply at the Stickney Water Reclamation Plant in Chicago

Complete mix aeration system for activated sludge process at the Eastman Kodak Company manufacturing facility in Rochester, NY .

(http://www.nywea.org/Clearwaters/pre02fall/302090.html)

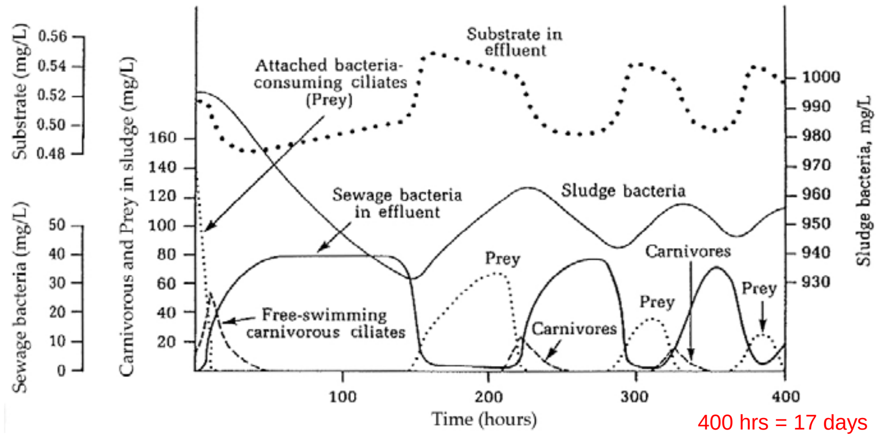
Activated-sludge aerator in Lansing, Michigan

Diffusers near bottom of empty aerator



Close-up

(*Source*: Davis & Cornwell, McGraw-Hill, 2008)



400 hrs = 17 days

(From Davis & Cornwell, 2008; their source: Curds, 1973)

Different organisms grow and decay depending on the nature of the sewage and its rate of flow. Note that biological processes take many hours to adjust to a changed "ecosystem".

Note: Cells = bacteria = micro-organisms are interchangeable words here.

Kinetics of cell growth and waste utilization:

In an activated-sludge reactor, there are two fundamental variables:
the amount of organic waste, denoted by S (as in Substrate), and
the concentration of bacterial cells, denoted by X.

Both are measured in mg/L.

The quantity S is also directly related to the BOD.
The higher the BOD in the sewage, the more food for the cells.

To determine their magnitudes, which may be functions of time, $S(t)$ and $X(t)$, we need to know their rate of growth and decay.

Location	TSS (mg/L)	BOD (mg/L)
Influent to plant	220	220
Effluent from primary, influent to secondary	95	140
Effluent from activated sludge unit	15	20

(Metcalf & Eddy, 1991 – as taken from Nazaroff & Alvarez-Cohen – Table 6.E.1)

Let us define:

r_S = rate of substrate consumption = decay rate of waste
[in mg of substrate/(L.day)]

r_X = rate of cell formation = growth rate – decay rate [in mg of cells/(L.day)]
= $r_g - r_d$

Empirical observation #1: The rate of cell growth r_g is proportional to the substrate consumption rate r_S, because the substrate is consumed by the cells to make more cells.

The coefficient of proportionality is defined as the yield and denoted by Y (no units).

Thus,

$$r_g = Y\ r_S$$

Typically, the value of Y is 0.6 or less because cells emit carbon dioxide and therefore put on as weight only a fraction of their food consumption.

Empirical observation #2:

The cell growth rate r_g is proportional to the cell concentration X, when all other variables are held unchanged, because the more cells there are, the more new cells can be manufactured.

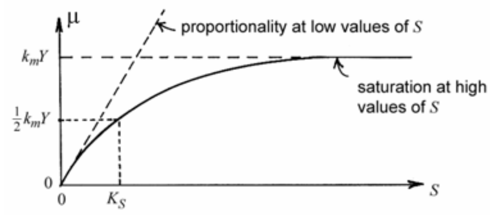
Thus,

$$r_g = \mu\ X$$

where the coefficient μ depends on other variables, such as the amount of substrate present, S.

Empirical observation #3: (Mihelcic & Zimmerman, pages 171-174; Mines & Lackey, pages 67-69)

The coefficient μ of proportionality depends on the substrate concentration as follows:
- At low S values, μ increases in proportion to increasing S, because the more food is available, the faster the cells multiply;
- At high S values, μ reaches a constant maximum value, because there is then a superabundance of food and cells cannot consume all of it right away.



This bimodal behavior is well captured by the so-called Monod kinetics:

$$\mu = \frac{k_m YS}{K_S + S}$$

where k_m is the growth constant (in /day), Y is the yield rate (ratio of cellular material generated per amount of substrate consumed), and K_S is called the half-saturation constant (in mg/L) because when $S = K_S$, $\mu = k_m/2$, which is at half of its maximum value. Put together, we have:

$$r_g = \frac{k_m SYX}{K_S + S} \qquad r_S = \frac{1}{Y} r_g = \frac{k_m SX}{K_S + S}$$

Empirical observation #4:

The death rate r_d of cells is proportional to the cell concentration X, because cells die in proportion to their number.

Thus,

$$r_d = k_d X$$

<u>Recycling</u>

To promote growth of the cells already adapted to the nature of the sewage, some fraction of the sludge collected at the bottom of the clarifier is recycled into the aerator.

Let us denote by Q_r the volumetric flow rate of sludge added to the inflowing rate of sewage Q_{in}, and by X_u the cell concentration inside the sludge collected at the bottom of the clarifier.

It goes without saying that X_u is expected to be significantly larger than the concentration X of cells in the aerator.

Table 6.E.2 Parameter Values for Conventional Activated Sludge Systems Using a Completely Mixed Flow Reactor

Parameter	Typical range	Typical value
Microbial parameters		
k_m (mg BOD_5 per mg VSS* per day)	2–10	5
K_s (mg BOD_5 per L)	25–100	60
Y (mg VSS* per mg BOD_5)	0.4–0.8	0.6
k_d (d^{-1})	0.025–0.075	0.06
Operational parameters		
Mean cell residence time, Θ_c (d)	5–15	
F/M (mg BOD_5 per mg VSS* per day)	0.2–0.6	
Loading (kg BOD_5 m^{-3} d^{-1})	0.8–1.9	
Total suspended solids (kg m^{-3})	2.5–6.5	
Hydraulic detention time, Θ (h)	3–5	
Recycle ratio, $R = Q_r / Q_{in}$	0.25–1	
BOD removal efficiency (%)	85–95	

Source: Metcalf & Eddy, 1991.

* VSS = Volatile Suspended Solids = biomass concentration

(Nazaroff & Alvarez-Cohen, page 351)