

CHEMICAL ENGINEERING

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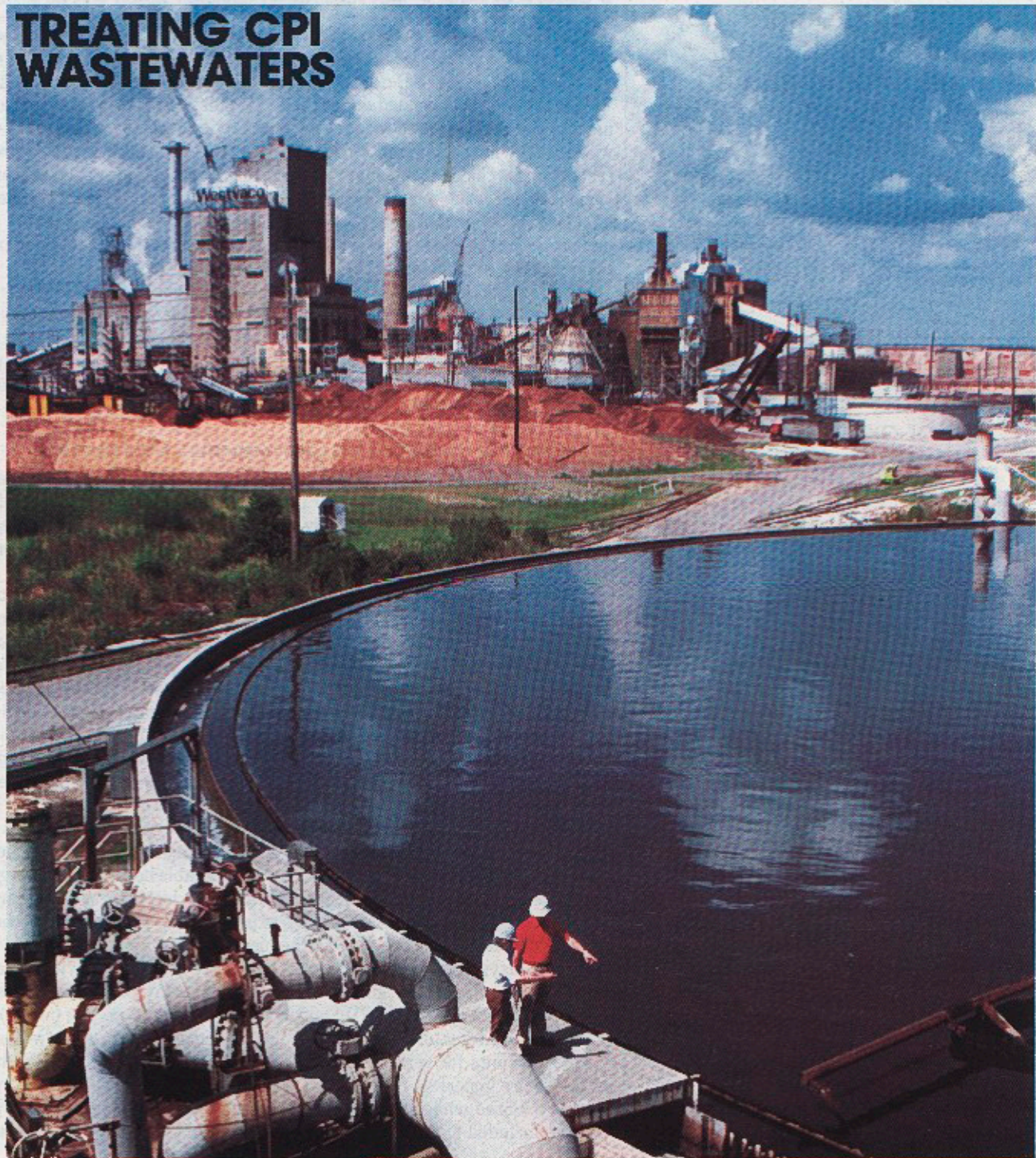
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A LOOK AT THE PROBLEM OF DEFECTIVE VALVES

EQUIPMENT LOCKOUTS SAVE LIVES

REVIEWS OF CHEMICAL ENGINEERING SOFTWARE

TREATING CPI WASTEWATERS



WASTEWATER TREATMENT

CPI wastewaters have to be treated before they can be released or reused. Some can be treated by conventional processes such as sedimentation, flotation and biological treatment. However, it may be necessary to pretreat certain streams (e.g., to remove toxic organics) and to polish the effluent by such methods as adsorption or oxidation.

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Effluent limits have become stricter in recent years, causing the chemical process industries to upgrade their wastewater-treatment systems and build new ones: Before 1972, limits in the U.S. applied only to soluble organics, suspended solids, and pH, plus a few specific chemicals and metals, and a plant could meet those limits by biologically treating its wastewaters. But now the limits on those pollutants are tighter; there are new restrictions on more than a hundred specific priority pollutants (mainly organic chemicals and heavy metals); and many plants are even required to assess the effects of their effluents on aquatic organisms. To meet these limits, plants have to employ sophisticated chemical and physical processes because biological treatment alone is not adequate.

Fig. 1 shows the processes presently used for industrial wastewater treatment, and how they tie together. This article will start with a brief overview of the wastewaters and the processes, and then describe each process in detail, explaining how it works, what it can accomplish, and how it should be applied. Costs will also be discussed. Overall, our aim is to explain how a combination of wastewaters can be economically treated so as to meet effluent limits.

The nature of chemical-process-industries wastewaters

A chemical process plant generates a number of wastewater streams—process wastewaters, cooling-tower blowdown, runoff and so on. Some of these streams may be treated by themselves, then reused in the plant, discharged as effluent, or injected into other treatment processes. Others may be combined into a single large flow and treated biologically.

How to treat a wastewater depends on its composition, concentration and flowrate, and on plant-specific concerns such as effluent limits, the abundance of water, the ability to reuse water, and the ability to sewer certain wastewaters to the publicly owned treatment works (POTW). But the object of any treatment is basically the same: to remove certain waste materials, as specified by regulations, so as to eliminate the harmful or unpleasant effects those wastes could have on the local environment.

What materials have to be removed? A wastewater stream may contain a great variety of chemicals, but only certain ones are specifically regulated, and the other contaminants are placed in broader categories:

1. *Soluble organics* include certain synthetic chemicals, as well as many natural products of animal and plant life. Though microorganisms will degrade most of them in the environment, they are undesirable because biomass growth can deplete the oxygen in the bodies of water to which they are discharged.

Soluble-organic content is typically expressed as biochemical or chemical oxygen demand. The five-day biochemical oxygen demand (BOD₅) is the amount of oxygen (mg/L) that has to be added to a wastewater to support the activity of its microorganisms over a period of five days. A related measure is chemical oxygen demand (COD), which is the amount of oxygen (mg/L), from potassium dichromate, needed to chemically oxidize a given wastewater.

COD accounts for certain nonbiodegradable organics. However, both BOD and COD are imperfect measures of organic content because some inorganics may be oxidized while some organics may not be. Nonbiodegradable organics are also included in the total organic carbon (TOC, mg/L), which is measured

by oxidizing all the organic matter to carbon dioxide. This category includes certain chemicals that cause tastes, odors and foaming in water supplies.

2. *Heavy-metal ions* such as mercury, chromium and lead, and other toxic ions such as cyanide, are subject to rigid effluent limits because they are poisonous.

3. *Acidity and alkalinity* are also disruptive to life, so acid or alkaline wastewaters have to be neutralized.

4. *Oils, greases and other floating materials* are esthetically undesirable, and should be removed completely.

5. *Nutrients* such as nitrogen and phosphorus are needed in biological treatment, but excess N and P have to be removed later: They make algae grow faster in lakes and ponds, which can deplete the oxygen in the water by a process known as eutrophication.

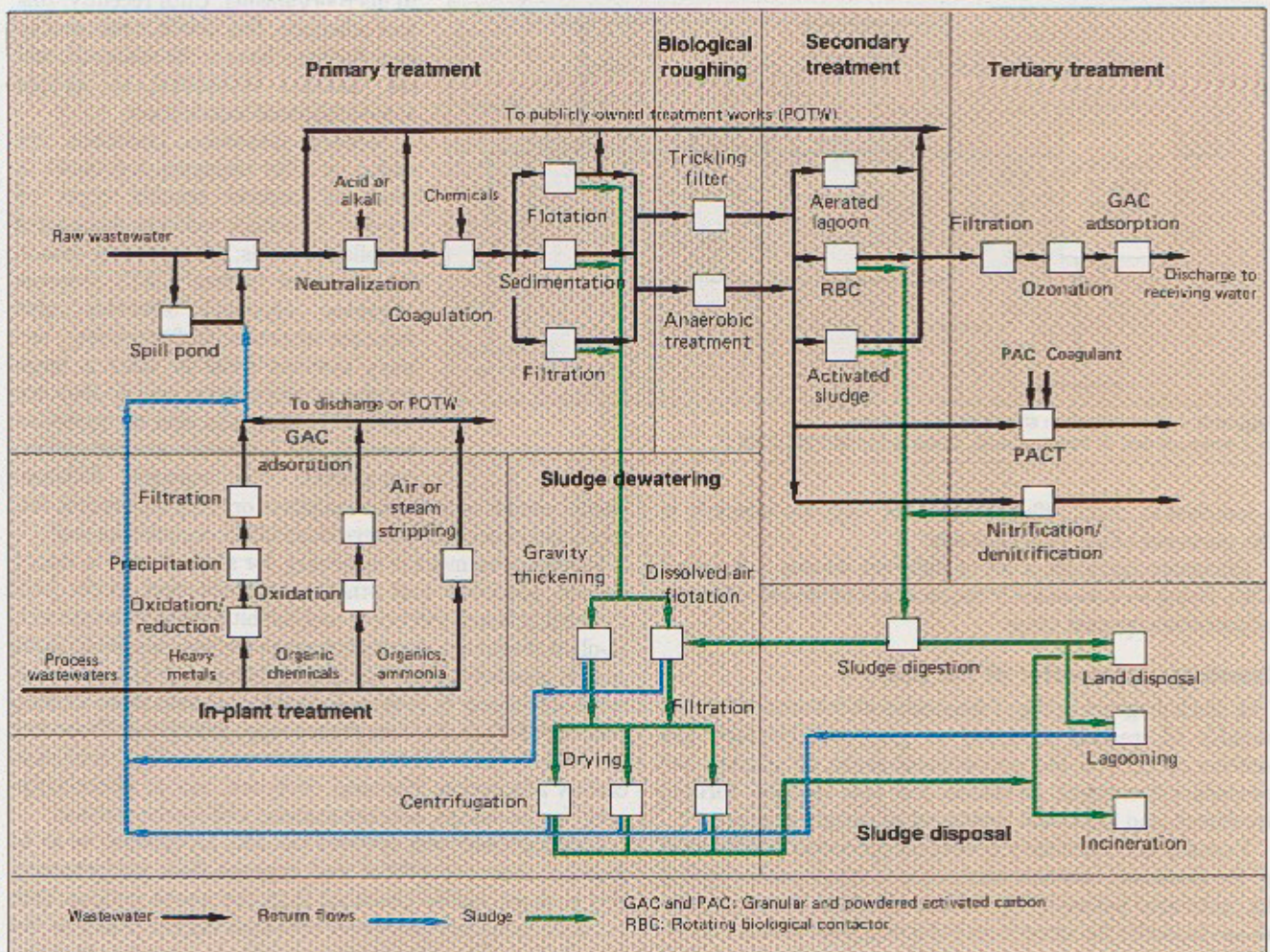


Figure 1 — Chemical process plants treat the bulk of their wastewaters biologically, but certain streams have to be pretreated by other methods

6. *Suspended and colloidal solids* make water opaque; a clear water is free of them. Also, suspended solids in an effluent will eventually settle, creating sludge banks downstream. Total suspended solids (TSS, mg/L) includes all solid materials, organic and inorganic. Volatile suspended solids (VSS, mg/L) includes only those that can be oxidized to gas at 550°C—most organics will be oxidized, while inorganics will remain as ash. An effluent often contains cells from the biological treatment process; these are largely volatile.

7. *Color, turbidity and odor* are unpleasant, and have to be removed. Color is a concern for pulp-and-paper and textile plants. Odor can be caused by materials such as sulfides; other volatile chemicals also pose an air-pollution concern.

8. *Priority pollutants* are the specific organic chemicals, heavy metals and ions that are individually regulated by the U.S. Environmental Protection Agency. There are more than

levels out the hour-to-hour variations in flows and concentrations. There should also be a spill pond, to hold up slugs of concentrated wastes that could upset the downstream processes. Neutralization, where required, follows equalization because streams of different pH partly neutralize each other when mixed. Oils, greases and suspended solids are removed by flotation, sedimentation or filtration.

Secondary treatment is the biological degradation of soluble organic compounds—from input levels of 50–1,000 mg/L BOD and even greater to effluent levels typically under 15 mg/L. This is usually done aerobically, in an open, aerated vessel or lagoon, but certain wastewaters may be digested anaerobically, in a pond or a closed vessel. After biotreatment, the microorganisms and other carried-over solids are allowed to settle. A fraction of this sludge is recycled in certain processes, but ultimately the excess sludge, along with the sedimented solids, has to be disposed of.

Many existing wastewater-treatment systems were built just for primary and secondary treatment—though a plant might also have systems for removing materials that would be toxic to microorganisms. Until recently, this was adequate, but now it is not, and so new facilities have to be designed, and old facilities retrofitted, to include some additional capabilities:

Tertiary treatment processes are added on after biological treatment in order to remove specific types of wastes: Filtration removes suspended or colloidal solids; adsorption by granular activated carbon (GAC) removes organics; chemical oxidation also removes organics. Unfortunately, tertiary systems have to treat a large volume of wastewater, and so they are expensive. They can also be inefficient because the processes are not pollutant-specific: For example, dichloro-

phenol can be removed by ozonation or GAC adsorption, but those processes will remove most other organics as well.

In-plant treatment is necessary for streams rich in heavy metals, pesticides and other substances that would pass through primary treatment and inhibit biological treatment. In-plant treatment also makes sense for low-volume streams rich in nondegradable materials, because it is easier and much less costly to remove a specific pollutant from a small, concentrated stream than from a huge, dilute one. Processes used for in-plant treatment include precipitation, activated-carbon adsorption, chemical oxidation, air- or steam-stripping, ion exchange, reverse osmosis and electro dialysis.

Existing treatment systems can also be modified so as to broaden their capabilities and improve their performance; this is more widely practiced than the above options. One example is adding powdered activated carbon (PAC) to the biological treatment process, to adsorb organics that the microorganisms cannot degrade—this is marketed as the PACT process. Another example is adding coagulants at the

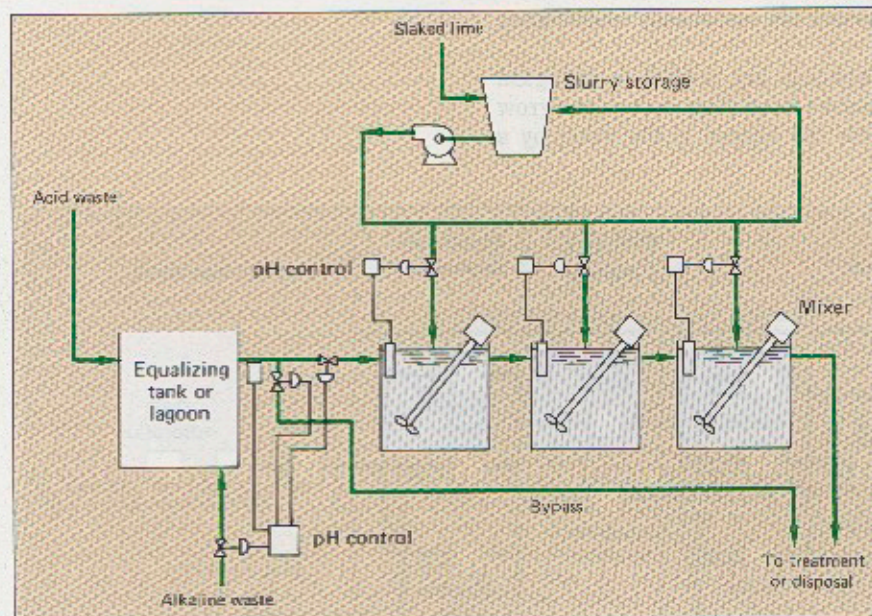


Figure 2—Neutralization should be carried out in a series of two or three vessels, using automatic pH control

a hundred of them; effluent limits for each are typically in the parts-per-billion ($\mu\text{g/L}$) range.

Obviously there are a lot of different wastes to be dealt with. Doing so economically requires a combination of several processes in most cases.

Treating wastewater at the plant

The block diagram in Fig. 1 illustrates an integrated system capable of treating a variety of plant wastewaters. The scheme centers on the conventional series of primary and secondary treatment processes, but also includes tertiary treatment and individual treatment of certain streams.

Primary and secondary treatment processes handle most of the dilute and nontoxic wastewaters; other waters have to be pretreated before being fed into this flow. These processes are basically the same in an industrial plant as in a POTW:

Primary treatment prepares the wastewaters for biological treatment. Large solids are removed by screening, and grit is allowed to settle out. Equalization, in a mixing basin,

end of the biological-treatment basin so as to remove phosphorus and residual suspended solids.

All these processes have their place in the overall wastewater-treatment scheme. Let us now consider them in detail.

Primary treatment

Primary treatment minimizes variations in wastewater flow and concentration and also removes a variety of pollutants. Certain wastewaters also have to be pretreated in the plant, to remove nondegradable or toxic pollutants.

Wastewaters that are to be biologically treated have to meet certain standards. This is what pretreatment and primary treatment have to achieve: < 2:1 variation in organics loading; pH 6-9; < 125 mg/L of suspended solids (TSS); < 15 mg/L of oils and greases; < 50 mg/L of sulfides; and < 1 mg/L, typically, of specific heavy metals. The processes

Lime (CaO or Ca(OH)_2) is the most common neutralizing agent for acids because it is inexpensive and easy to add, but it requires a long reaction time and can lead to problems with calcium sulfate precipitation. Beds of limestone can effectively neutralize variable-strength acids.

Most strong acids can be used to neutralize alkaline wastewaters; sulfuric acid usually is the cheapest. If available, fluegases having a high CO_2 content (> 14%) can be used.

The low buffering capacity of most wastewaters is a big problem in neutralization because small variations in acid or alkali dosage can lead to large variations in pH. For this reason, it is advisable to have a two- or three-stage system, with automated pH control, as in Fig. 2, or to neutralize batchwise if the flow is low enough — under 100,000 gal/d.

4. Sedimentation removes suspended solids. Certain particles, as in pulp-and-paper wastes or domestic sewage, ag-

Table 1 — Aerobic and anaerobic biological treatment removes up to 95% of the BOD in a wastewater

Treatment process	Retention time, d	Depth, ft	Biomass (x _v), mg/L	BOD ₅ in feed, mg/L	BOD ₅ removal, %	Conditions
Aerobic						
Activated sludge	0.16-0.33	12-16	2,000-3,000	100-3,000	85-95	Prevent sludge bulking
Extended aeration	0.5-1	12-16	3,000-4,000	100-3,000	85-95	F/M < 0.2
Rotating biological contractor	N.A.	N.A.	N.A.	50-500	80-95	Loading 1.5-8 lb BOD/ft ² -d
Trickling filter	N.A.	15-30	N.A.	500-3,000	50-60	Loading 0.1-0.5 lb BOD/ft ³ -d
Aerated lagoon (aerobic)	0.5-3	8-16	≈0.5 BOD in feed	50-750	50-70	Well-mixed
Aerated lagoon (facultative)	3-10	8-16	50-100	50-250	80-95	Surface mixing
Anaerobic						
Anaerobic reactor	0.5-30	N.A.	5,000-12,000	1,500-10,000	70-95	Loading 0.1-0.95 lb BOD/ft ³ -d
Anaerobic pond	5-50	8-15	<25	500-2,000	50-80	Loading 250-4,000 lb BOD/acre-d
Facultative pond	7-50	3-8	<25	50-250	70-95	Loading 20-50 lb BOD/acre-d; algae 10-50 mg/L
BOD: Biochemical oxygen demand			F/M: Food-to-microorganism ratio		N.A.: Not applicable	

used for this are fairly simple, but there are challenges in operating them properly:

1. Screening removes large solids, and is widely applied in the canning, brewing, and pulp and paper industries. Depending on the application, bar racks, static screens, rotary-drum screens or vibrating screens may be used.

2. Equalization minimizes hour-to-hour variations in wastewater flow and composition, and prevents shock loads from upsetting the downstream processes. The equalization basin may be designed with a variable or constant volume; it is usually mixed, to ensure adequate equalization and to prevent solids from settling out.

3. Neutralization generally is achieved by mixing some acid or alkali with the wastes, but how much is required depends on the upstream and downstream processes. Aerobic treatment neutralizes alkalinity and buffers itself as it produces carbon dioxide; for each 1 mg of BOD₅ removed, about 0.5 mg of alkalinity as CaCO_3 is neutralized. Also, if both acid and alkaline streams are fed into the equalization basin, they will neutralize each other to some extent.

glomerate as they settle, which affects the settling rate. This is termed flocculant settling. Particles such as sand, flyash and coal do not agglomerate; this is discrete settling. There are various types of settling tanks; in most, solids are removed from the bottom mechanically.

In general, sand and other grit should be removed early on, so as to prevent abrasive wear on pumps, clogging of pipes, and accumulation in vessels downstream. In a shallow grit chamber, a horizontal velocity of 1 ft/s allows grit to settle but organic particles to pass through to a clarifier.

Clarifiers may be rectangular or circular; the circular ones are preferred because they require less maintenance. For high-efficiency solids removal, tube and parallel-plate separators are used.

5. Flotation of oils, greases and other materials allows them to be skimmed off the wastewater. Gravity separation is used when the oil globules are large enough to float to the surface in a reasonable time. There are two basic types of gravity separators: the API separator, basically a large skimming tank, and the corrugated-plate interceptor, which

has inclined parallel plates that promote coalescence of small globules into larger ones.

Air flotation enhances the separation of floating materials by attaching air bubbles to the particles. In dissolved-air flotation (DAF), fine air bubbles are generated by injecting air into the water under pressure, then reducing the pressure. In induced air flotation (IAF), air is mechanically entrained, or introduced through fine-holed diffusers. Flotation will not remove dispersed or emulsified oil, however, unless coagulants are added.

Now, at this point, our wastewater still contains soluble organics and inorganics, plus colloidal solids and other suspended organic matter. Although the solids can be filtered out, usually this is not necessary.

High concentrations of volatile organics should be removed before aerating the wastewater, because aeration

Table II — Reaction-rate coefficients for selected organic wastewaters

Wastewater source	Reaction-rate coefficient (k), 1/d	Temperature, °C
Vegetable tannery	1.2	20
Cellulose acetate	2.6	20
Peptone	4.0	22
Sulfite paper mill	5.0	18
Organic phosphates	5.0	21
Vinyl acetate monomer	5.3	20
Organic intermediates	5.8	8
	20.6	26
Viscose rayon and nylon	6.7	11
	8.2	19
Domestic sewage (solubles)	8.0	20
Petroleum refinery	9.1	20
Polyester fiber	14.0	21
Formaldehyde, propanol, methanol	19.0	20
High-nitrogen organics	22.2	22
Potato processing	36.0	20

would release them into the atmosphere. This is best done in the plant, but can instead be done after primary treatment.

Biological treatment

In biological treatment, bacteria and other microorganisms break down and metabolize the soluble and colloidal organic materials in the wastewater, thereby reducing the BOD and COD to 10–100 mg/L. Not all the organics are degraded, though. While most could be degraded, given enough time and the right bacteria, these cannot always be provided.

Biological treatment usually is done aerobically. Here, the water is aerated and the microorganisms convert the organic carbon to carbon dioxide and new cells. In anaerobic treatment, the organisms produce methane as well as CO₂. In either process, the cell matter, and certain nondegradable materials, settle in the water to form a sludge.

Table I describes the principal biological-treatment processes and what they accomplish. Which one to select depends on the character, strength, volume and variability of the wastewater, and on factors such as operator skill:

1. The activated-sludge process, carried out in an aerated vessel, reduces soluble BOD to less than 10–15 mg/L, and

total BOD, including suspended solids, to less than 30 mg/L. It is often preferred in cases where a high effluent quality is desired, land is limited, and wastewater flow is above 100,000 gal/d. However, because the process has a short retention time, it takes skill to operate and is sensitive to toxic and hydraulic shocks. It also requires disposal of excess sludge.

Extended aeration is the activated-sludge process operated with a longer retention time. It can reduce BOD below 10 mg/L, but solids carryover may run as high as 50 mg/L. To clear this effluent usually requires coagulation or filtration. Because of its 12–24-h retention time, the process usually is considered only for flows under 1 million gal/d.

2. An aerated lagoon can reduce soluble BOD to less than 25 mg/L, and total BOD to less than 50 mg/L. A lagoon is insensitive to loading variations because it has such great volume, but it requires acres of land and, because it is open, it

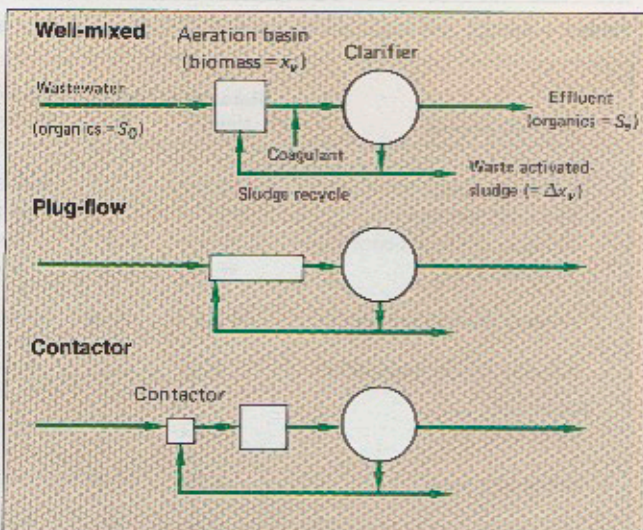


Figure 3 — The activated-sludge process can be carried out in well-mixed or plug-flow aeration basins

is less efficient in the winter. Also, solids carryover can exceed 100 mg/L, so the effluent may have to be settled or filtered. A facultative lagoon is an aerated one in which some of the solids decompose anaerobically on the bottom. This removes more of the BOD; and odors produced at the bottom are generally removed by the aerobic organisms on top.

3. Anaerobic ponds operate without aeration, and typically are followed by an aerobic treatment. Facultative ponds get some air, and are more effective because they support both anaerobic and aerobic organisms. But both can release odors, and could not be used in many locations.

4. Trickling filters and rotating biological contactors (RBCs) are reactors in which a film of microorganisms oxidizes the wastewater. High-rate trickling filters reduce BOD by 60–85%; roughing filters, operated at high organic loadings, reduce BOD by 50–60%. RBCs are as efficient as the activated-sludge process, though they are smaller, use much less energy, and are easier to operate. They are, however, more sensitive to BOD variations.

5. Anaerobic digestion, in a closed reactor, efficiently removes soluble and colloidal organics from concentrated streams, and it reduces nitrates to nitrogen gas. Even when

run with very little energy input, the process can remove 70–90% of the BOD, and so it may be applied to pretreating soluble-organic wastewaters ahead of aerobic treatment. Like activated sludge, this process requires skill to operate and is sensitive to toxic and hydraulic shocks.

Aerobic treatment

Aerobic wastewater treatment involves two biochemical reactions, one for the growth and normal metabolism of the bacteria and other cells, and another for their oxidation of their own cell material (endogenous respiration). For the process to work properly, cells must be allowed to grow faster than they are used up (this produces sludge):

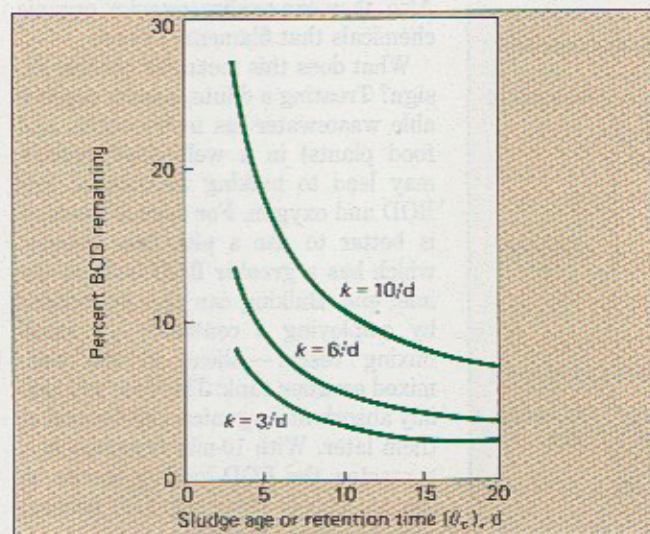
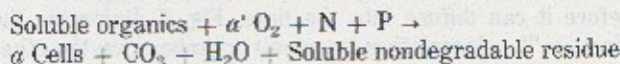
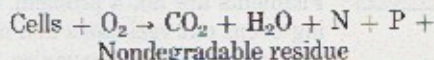


Figure 4 — The rate of organics decomposition declines as more organics are removed and as the sludge retention time increases



In the first reaction, α is the fraction of organics removed that is converted to new cells (mg VSS/mg organics), and α' is the amount of oxygen (mg O_2 /mg organics) needed for this.

The rate of the second reaction is b . This is the fraction of degradable biomass oxidized per day. The overall biomass is considered to be volatile suspended solids; the VSS concentration is x_v . Most of the biomass is readily degradable; the degradable fraction, denoted as y , is typically 80%. The actual fraction in the process depends on the conditions, though. For instance, if the retention time is increased, more of the degradable biomass is oxidized, and the fraction of nondegradable biomass in the vessel increases.

The removal of a single component typically follows zero-order kinetics to a low residual level, which means that the rate of removal per unit of biomass is more or less constant. This reaction rate, k (units of 1/d), may be considered the fraction of BOD, COD or TOC removed per day of retention. Table II lists values of k (BOD) for various wastewaters.

A mixture of organics, however, follows first-order kinet-

ics, so the rate of removal per unit of biomass declines as the organics are consumed. The extent of removal may be calculated as follows. Here, the rate constant is K (mg BOD or COD/mg VSS-d):

$$\text{Plug flow: } S_e/S_0 = e^{-Kt} (x_v/S_0)$$

$$\text{Well mixed: } (S_0 - S_e)/(S_0) = Kt (x_v/S_0)$$

where S_0 is the influent BOD or COD (mg/L), S_e is the effluent, BOD or COD, x_v/S_0 is the organics loading, and t is the retention time (d). The amount (mg/L) of BOD or COD removed is denoted S_r .

Of course, the reaction rates above depend on temperature. Over the range 4–31°C, the rate coefficient varies as:

$$K(T) = K(20^\circ\text{C}) \theta^{(T-20^\circ\text{C})}$$

where θ has a value between 1.03 and 1.10. Rate also depends

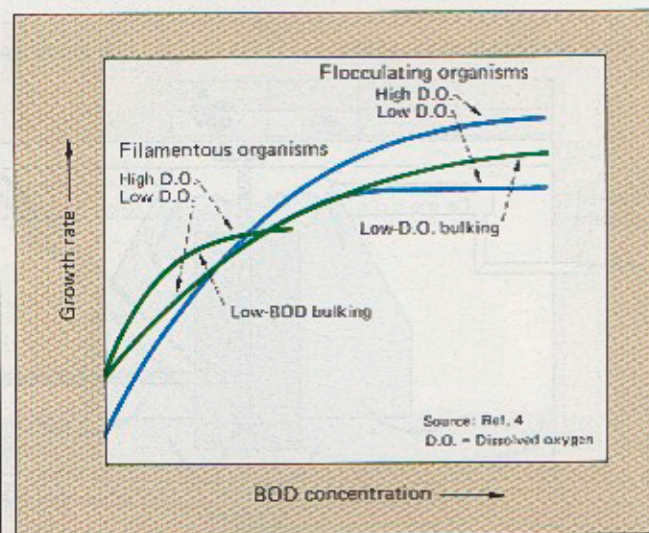


Figure 5 — The filamentous organisms that cause sludge bulking will outgrow the flocculating ones when there is too little oxygen or BOD

on the pH; generally, the optimal pH is in the range 6.5–8.5.

Sludge is excess biomass. The amount produced, Δx_v , is:

$$\text{Sludge produced: } \Delta x_v = \alpha S_r - b y x_v$$

plus any nondegradable solids that simply pass through biological treatment. As for heavy metals, they not only inhibit the bacteria, but some are adsorbed by the sludge, making it difficult to dispose of.

The amount of oxygen needed for endogenous respiration is about 1.4 mg/mg VSS oxidized. Thus the overall oxygen requirement (mg/L processed) may be calculated as:

$$\text{Oxygen} = \alpha' S_r + 1.4 b y x_v$$

This means dissolved oxygen, so of course an excess of air or oxygen must be provided by aeration or other means. Aeration also adds to organics removal by stripping off volatile compounds.

Domestic wastewaters usually have an excess of nutrients, but industrial ones often are deficient. The requirements for nitrogen and phosphorus may be estimated as:

$$\text{N} = 0.123 (0.8/y) \Delta x_v + 0.07 (0.8/y-1) \Delta x_v$$

$$\text{P} = 0.026 (0.8/y) \Delta x_v + 0.01 (0.8/y-1) \Delta x_v$$

Now let us consider specific biological processes, beginning with activated sludge.

The activated-sludge process

In an activated-sludge system, soluble organics are degraded by bacteria in an aerated basin, and biomass is carried over with the effluent into a clarifier, where solids are allowed to settle and then are concentrated and removed. Part of the settled sludge is drawn off as waste; the rest is recycled to the aeration basin, to maintain a high concentration of bacteria. Fig. 3 shows two well-mixed systems, in which aeration occurs in a mechanically agitated vessel, plus a plug-flow system, in which the long, narrow basin is agitated by the air introduced at the bottom. Which system to select, and how large to make the reactor, depends on the wastewater and the kinetics of its decomposition.

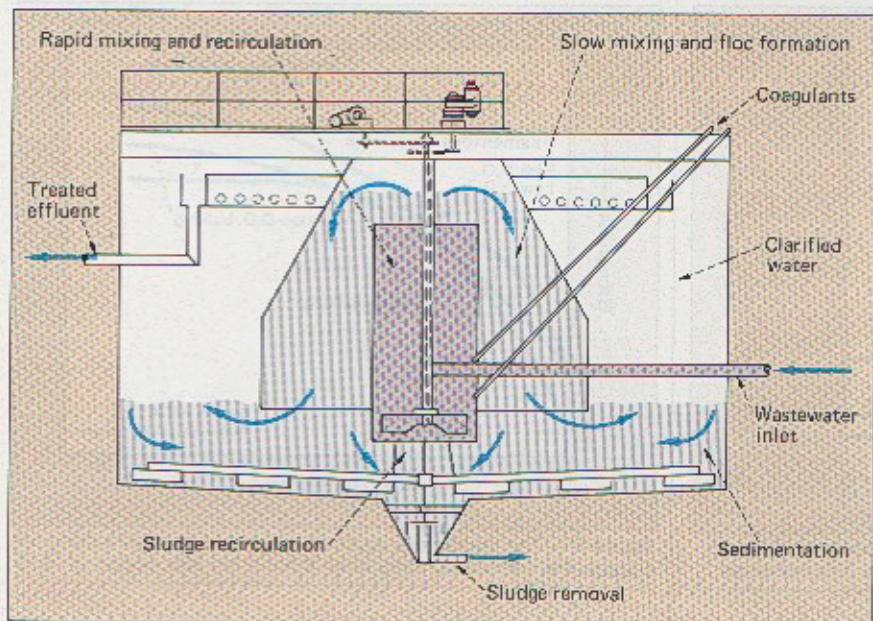


Figure 6 — A reactor-clarifier is designed for both coagulation and settling

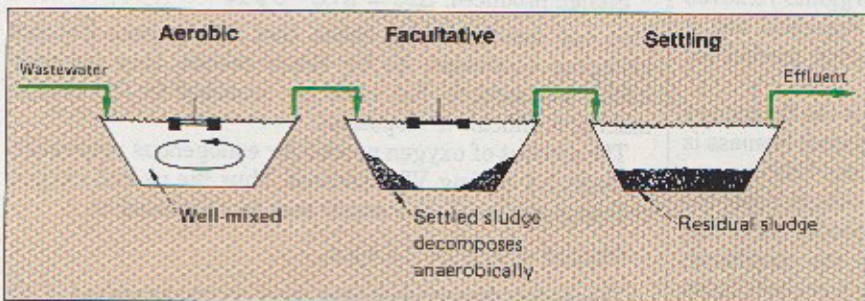


Figure 7 — An aerated lagoon is aerobic if it is well-mixed, facultative if solids are allowed to decompose on the bottom

Generally, the organic loading of the process may be described by the ratio of food to microorganisms, F/M (mg BOD/mg VSS), or by the sludge age, θ_c , which is the average length of time the organisms are retained in the system before being drawn off as waste sludge:

$$\text{Loading: } F/M = S_0 / x_p t \quad \text{Sludge age: } \theta_c = x_p t / \Delta x_p$$

The organic loading varies inversely with the sludge age, and so does the rate of organics removal — represented by the slope of the curves in Fig. 4. This means that going from 90% BOD removal to 95% can require more reactor volume than going from 0 to 90%.

For the process to work properly, the sludge has to settle easily in the clarifier, and it will if the bacteria agglomerate together into tight flocs. An excess of filamentous organisms, though, results in bridged or diffused flocs that settle very slowly. This very common problem is called sludge bulking. Growth of filaments is favored when dissolved oxygen or BOD is too low: The filamentous organisms have more surface area, so they use up the limited oxygen or food before it can diffuse into the flocs. Fig. 5 illustrates the kinetics. The flocculating (zoogloal) organisms, on the other hand, are favored by high dissolved oxygen and high BOD.

Also, they can oxidize complex organic chemicals that filaments cannot.

What does this mean for reactor design? Treating a dilute, readily degradable wastewater (as in breweries and food plants) in a well-mixed reactor may lead to bulking because of low BOD and oxygen. For such a waste, it is better to use a plug-flow reactor, which has a greater BOD level at the inlet end. Bulking can also be avoided by employing a contactor—a small mixing vessel—ahead of the well-mixed aeration tank: The flocs will rapidly absorb the organics, and feed off of them later. With 10-min retention in a contactor, the BOD loading can be as low as 0.1 mg BOD/mg VSS without causing sludge bulking.

As for more complex organics, they are best treated in well-mixed reactors: Filaments are not a problem, and mixing evens out variations and helps prevent upsets. If the organics are very concentrated, though, some of the biomass will exist as dispersed particles that will pass through a clarifier and result in too great an effluent TSS and BOD. Too low a temperature, or too high a dissolved-inorganics level, will cause the same problem. In such a case, the effluent has to be coagulated, either ahead of the clarifier or in a reactor-clarifier as shown in Fig. 6.

The activated-sludge process removes certain organic priority pollutants at efficiencies of 95% or more, leaving effluent levels below 30 $\mu\text{g/L}$.

Some organics are removed solely by biodegradation, but others are stripped out by air to varying degrees.

Pollutants that can be 95% biodegraded include nitrobenzene, 2,4-dichlorobenzene, 2,4-dinitrobenzene, benzidine, acrolein, acrylonitrile, phenol, pentachlorophenol, phenanthrene and naphthalene. Ones whose removal is 5-50% due to

stripping include benzene, 1,2-dichlorobenzene, ethylbenzene, toluene and ethyl acetate, plus di-, tri- and tetrachloromethane. Then, certain volatile compounds, such as 1,2-dichloroethane, 1,1,1-trichloroethane, trichloroethylene and 1,2-dichloropropane, are 95% removed by air-stripping alone. Such stripping is a problem because these pollutants should not be released into the atmosphere.

Aerated lagoons

An aerated lagoon is a basin, 8–16 ft in depth and up to several acres in area, that is oxygenated by means of agitation or air diffusion so as to promote biodegradation of soluble organics. In an aerobic lagoon, the dissolved oxygen and suspended solids are well-mixed throughout (using 14–20 hp/million gal), and the microorganisms are aerobic. In a facultative lagoon, only the surface is agitated (4–10 hp/

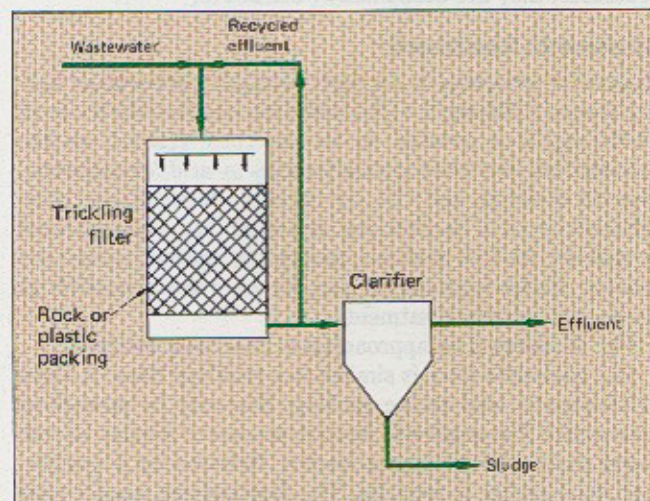


Figure 8 — A trickling filter is a packed-bed biological reactor, often with some provision for recycle

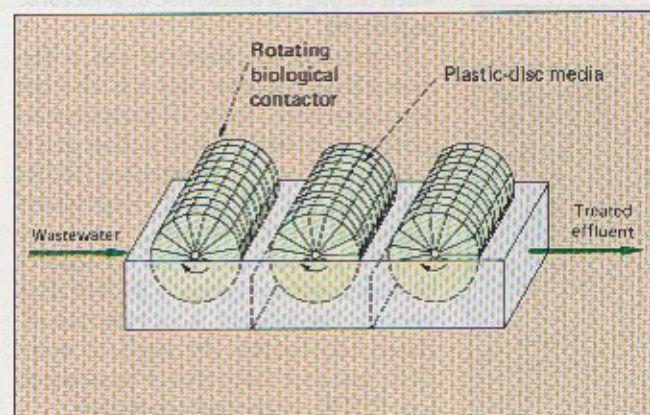


Figure 9 — Rotating biological contactors (RBCs) are aerobic reactors usually operated in series

million gal), and some of the solids settle at the bottom. Here, they are decomposed by anaerobic organisms; methane and other products are oxidized by the aerobic organisms in the water above.

Fig. 7 illustrates an optimal lagoon configuration: an aerobic lagoon, followed by a facultative one and then by a

settling lagoon, if needed, to clear the effluent of suspended solids. The aerobic lagoon degrades soluble organics, and greatly increases the concentration of biomass. Retention time is 1–3 d. The facultative lagoon removes residual BOD, and most of the suspended solids, in a retention time of 3–6 d. If effluent suspended solids must be below 50 mg/L, a settling lagoon may be necessary; such a lagoon typically is large enough to hold ten years' worth of residual sludge.

Such a lagoon system is comparable in removal efficiency to an activated-sludge process, but while it does not require continuous sludge removal, it does require acres of land.

Aerobic lagoons are used also to pretreat wastes before their discharge to a municipal sewer for treatment at the POTW. Here, it is important that the flow velocity in the sewer be great enough to prevent the suspended solids from settling out.

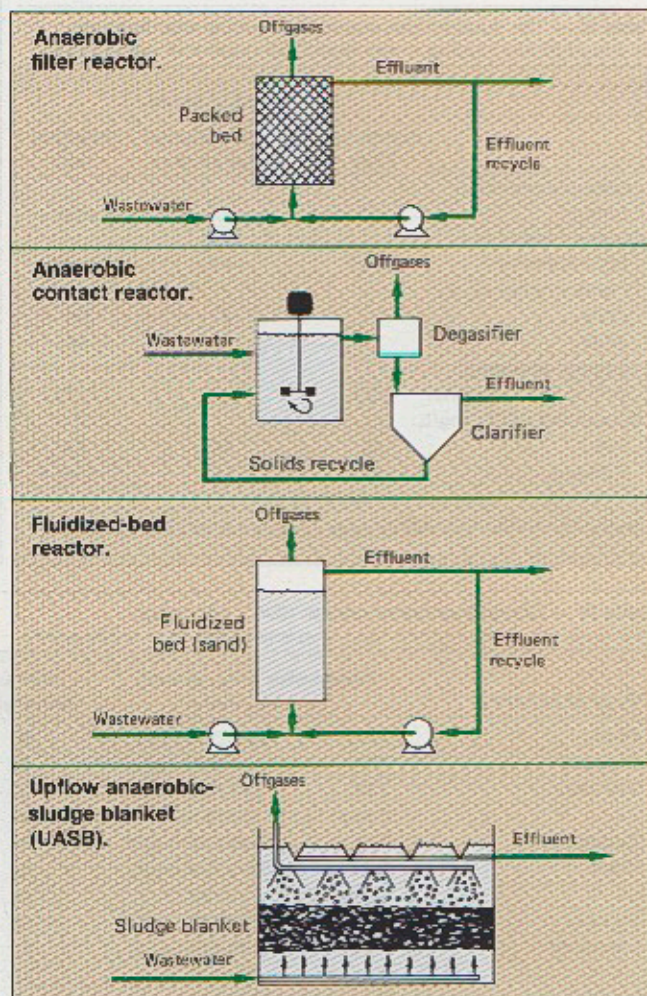


Figure 10 — Anaerobic wastewater treatment is carried out in various types of reactors

Trickling filters

A trickling filter is a packed-bed biological reactor in which the plastic or rock packing is covered by a film, or slime, of aerobic microorganisms. As wastewater passes through the bed, oxygen diffuses in, organics are decomposed by the

slime, and CO₂ is given off. Older designs use 2½-4 in. rock packed to a depth of 3-8 ft, but plastic mass-transfer packing is now preferred, as it can be packed to a depth of 40 ft, and can handle up to 4 gal/ft²-min.

Trickling filters cannot economically remove more than about 85% of the BOD, but in general they are easier and less costly to operate than activated-sludge processes. Also, they can pretreat high-strength wastewaters very economically. A filter operating at 50% BOD removal can handle several times the BOD loading of one operating at 85%. In such a case, part of the effluent has to be recycled, as in Fig. 8, so as to maintain aerobic conditions.

Rotating biological contactors

A rotating biological contactor (RBC), illustrated in Fig. 9, is made up of numerous large plastic discs mounted on a

rotating shaft with about 40% of their volume submerged in a tank of wastewater. The discs support a 1-4-mm film of microorganisms. As the contactor rotates, it carries a certain amount of wastewater through the air, enabling the microorganisms to oxidize the soluble organics. In the water, shearing forces strip off excess biomass; this is collected downstream in a clarifier.

The disc medium typically is high-density polyethylene having a surface area of about 37 ft²/ft³. A single RBC unit can be as much as 12 ft in diameter and 25 ft long, and can have as much as 100,000 ft² of surface provided by hundreds of discs. An RBC system usually consists of 2-4 RBCs in series: The BOD-removal kinetics are better when the reaction is carried out stagewise, and the later stages also promote conversion of ammonia to nitrate.

Because RBCs use less energy than do activated-sludge processes, they are economically attractive.

Table III — The fluidized-bed reactor is the most effective type for anaerobically treating a very-high-COD paper-mill wastewater

	Anaerobic reactor		
	Anaerobic filter	Upflow anaerobic-sludge blanket	Fluidized bed
Hydraulic retention time, d	1.0	2.9	0.35
Organics loading, kg COD/m ³ -d	10-15	4-5	35-48
Organics removed, %:			
COD	77	87	88
BOD	77	88	89
Methane generated, m ³ /kg COD removed	0.31	0.28	0.35
Suspended solids, mg/L:			
Feed	33	56	29
Effluent	195	238	110

Basis: Paper-mill foul condensate, COD = 13,700 mg/L

Anaerobic treatment

Anaerobic treatment is for high-strength wastewaters having at least 1,500 mg/L COD, and it can handle COD levels of 10,000 mg/L or greater. In an anaerobic reactor, soluble organics are converted to volatile acids by acid fermentation, then to methane and CO₂ by methane fermentation (two different types of bacteria are involved). The gas generated is typically 65-75% methane, and can be burned to heat the reactor. Sludge is produced, also, but only about one-fifth as much as in aerobic treatment.

Fig. 10 shows four approaches to anaerobic treatment:

The anaerobic filter is similar to a trickling filter. A slime of biomass is held on the packing; flow may be upward or downward. The anaerobic contact process is similar to activated sludge: It employs a reactor, followed by a clarifier, and some sludge is recycled. The fluidized-bed reactor uses sand as a surface for microorganisms to grow on. The UASB (upflow anaerobic-sludge blanket) passes wastewater upward through a dense floc of anaerobic organisms.

In general, the fluidized bed is the most efficient reactor, but it is also the most expensive. Table III compares its performance with that of a filter and a UASB on a very concentrated (13,700 mg/L COD) but easily degradable paper-mill foul condensate.

COD-removal efficiencies for anaerobic treatment are typically 85-90%. But because the influent is so rich, the effluent may contain 100 mg/L or more COD, and so it may have to be sewered to a POTW, or treated aerobically.

Removing nitrogen biologically

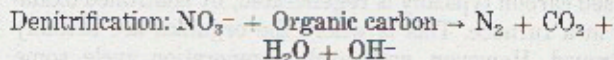
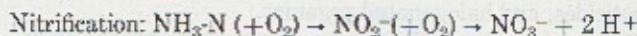
Organic nitrogen in wastewater may be partly or fully converted to ammonia by biological treatment, but this ammonia may have to be removed downstream, and a stream rich in NH₃ or other nitrogen compounds may require modifications in the biological process.

Table IV — Granular-activated-carbon (GAC) adsorption effectively removes organics from a variety of industrial wastewaters

Type of industry	Wastewater TOC, phenol, or color index	Average removal, %	Carbon usage, lb/1,000 gal
Food	TOC 25-5,300 mg/L	90	0.8-345
Tobacco	TOC 1,030 mg/L	97	58
Textiles	TOC 9-4,670 mg/L	93	1-246
	Color 0.1-5.4	97	0.1-83
Apparel	TOC 390-875 mg/L	75	12-43
Paper	TOC 100-3,500 mg/L	90	3.2-156
	Color 1.4	94	3.7
Printing	TOC 34-170 mg/L	98	4.3-4.6
Chemicals	TOC 19-75,500 mg/L	85	0.7-2,905
	Phenol 0.1-5,325 mg/L	99	1.7-185
	Color 0.7-275	98	1.2-1,328
Petroleum refining	TOC 38-4,400 mg/L	92	1.1-141
	Phenol 7-270 mg/L	99	6-24
Rubber and plastics	TOC 120-8,375 mg/L	95	5.2-164
Leather	TOC 115-9,000 mg/L	95	3-315
Stone, clay, glass	TOC 12-8,300 mg/L	87	2.8-300
Primary metals	TOC 11-23,000 mg/L	90	0.5-1,857
Fabricated metals	TOC 73,000 mg/L	25	606

TOC = Total organic carbon

Ammonia is removed biologically by conversion to nitrate and then to nitrogen gas. This is done by different organisms, in two steps:



Nitrifying organisms are inhibited by various inorganics and organics present in industrial wastewaters. Nitrification is inhibited, too, by free ammonia and free nitrous acid. These are formed when the pH is too high, and so proper pH control is very important. The optimal pH is 7.0-7.5. Note that nitrification generates H^+ , enough to neutralize 7.14 mg alkalinity (as CaCO_3)/mg $\text{NH}_3\text{-N}$ oxidized. Thus, lime or sodium bicarbonate may have to be added.

It is also important to provide enough dissolved oxygen; 2 mg/L is recommended for maximum nitrification. Denitrification, in contrast, is done under anoxic conditions — i.e., in the absence of free oxygen. It also generates alkalinity, but only half as much as is lost in nitrification.

Thus, nitrification-denitrification requires a sequence of aerobic and anoxic treatment, with organic carbon present, and the right pH. It can be done in an activated-sludge reactor by limiting oxygen so as to have anoxic conditions in the center of the flocs. A simple and economical approach is to use a circular channel, and position aeration equipment so as to create aerated and anoxic zones. Such an oxidation ditch is shown in Fig. 11. Another way is to have a single aeration-sedimentation vessel, but switch the air on and off so as to yield aerobic and anoxic conditions in turn. A more complex way is to have separate basins for nitrification and denitrification.

Overall, biological processes are about 70-95% efficient, and can remove of all forms of nitrogen, but they require a long retention time, and are sensitive to shock loads, toxics and temperature.

Chemical and physical ammonia removal

Ammonia may also be removed by air stripping, ion exchange or chlorination. In air stripping, caustic soda (NaOH) or lime is added to the water so as to increase its pH to 10.5-11. This releases ammonia gas, which is then stripped off by contacting the water with air. Generally, this is done in a cooling tower, so there may be efficiency problems and icing in the winter, and CaCO_3 can deposit in the tower if lime is used. If ammonia is instead removed in a stripping column, it can be recovered as ammonium sulfate, by reaction with H_2SO_4 , rather than being released to the atmosphere [9]. In general, air stripping is about 50-95% efficient, and costs about 30% more than biological nitrogen removal [14].

Ammonia may also be removed by ion exchange, using a natural zeolite (clinoptilolite) that selects NH_3 over Ca , Mg

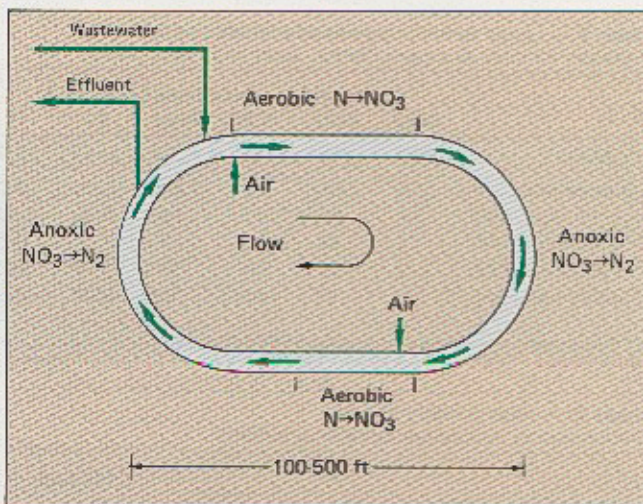


Figure 11 — In an oxidation ditch, ammonia is biologically nitrified in the aerobic section, then denitrified in the anoxic section

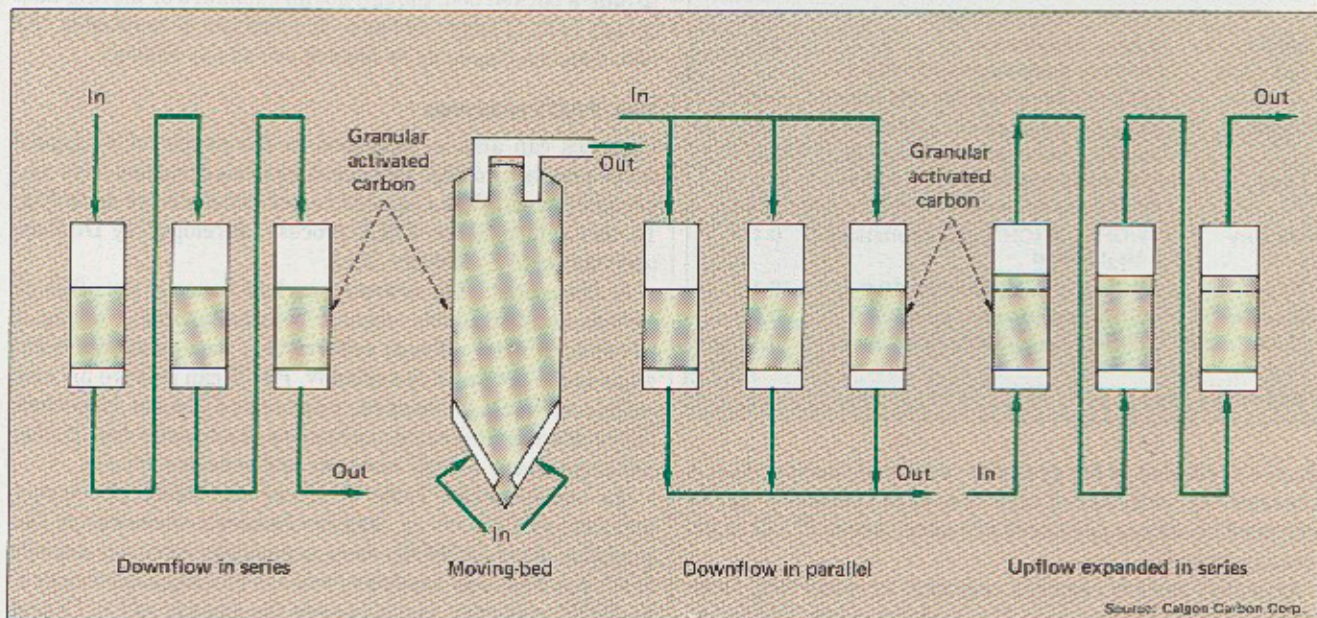


Figure 12 — Adsorption is carried out in fixed, fluidized or expanded beds of granular activated carbon

and Na ions, though those minerals do reduce its NH_3 capacity [10]. The zeolite is regenerated with sodium or calcium hydroxide at high pH; the ammonia can then be air-stripped from the water, and the regenerant recovered. Overall, ion exchange is about 90-97% efficient, and costs about 55% more than biological nitrogen removal.

Chlorine oxidizes ammonia to nitrogen gas but also produces mono- and dichloroamines. The breakpoint, at which chloroamine concentration is at a minimum, occurs at a chlorine:ammonia ratio of 8-10 (7.6 in theory). To minimize nitrate and trichloride formation, pH should be held near 7. Operated properly, chlorination is 90-100% efficient.

Activated-carbon adsorption

Organic chemicals that are not readily biodegradable can be removed by treating individual streams or the biological

ever, extremely large molecules, such as polymers, may be physically too large to fit in the pores. The most typical applications are in removing color-producing compounds, pesticides, and halogenated organics.

Used carbon typically is regenerated, by controlled oxidation in a furnace. This is where the organics are actually destroyed. However, with each regeneration cycle some carbon is burnt up, and because the effective surface area is reduced, the adsorption capacity per pound declines.

Adsorption by granular activated carbon typically is done either in a series of fixed or expanded beds, or in a single moving bed, as illustrated in Fig. 12. The advantage of the moving bed is that carbon addition and regeneration may be done continuously (fluidized bed) or nearly so (pulsed bed).

Predicting the performance of GAC adsorption requires a batchwise adsorption-isotherm test. This determines the

amount of an organic that can be adsorbed, per pound of carbon, and thus indicates whether adsorption can be done effectively and economically. Before actually designing a system, it is also advisable to run a pilot-plant test; the regeneration should also be piloted.

In general, GAC adsorption can remove over 90% of the organics in many industrial wastewaters. Table IV, a summary of numerous adsorption-isotherm tests, lists the average adsorption reported for wastewaters from various industries.

Note that a bed of GAC will often support biological activity. This can be good or bad. On the one hand, the microorganisms can remove up to 2 lb of COD, or even more, for every 1 lb removed by the carbon [20]. But if the influent BOD is above 50 mg/L, anaerobic activity can lead to odor problems, and aerobic activity can generate enough biomass to plug a packed bed, though not an expanded or moving bed. In any case, if large amounts of solids are generated in the bed, they may have to be filtered out of the effluent.

The PACT process

Organics can also be adsorbed in the course of biological treatment by mixing powdered activated carbon into the aeration basin. When applied to activated sludge as in Fig. 13, this is termed the PACT process (developed by Du Pont and marketed by Zimpro, Inc.).

In the process, the activated carbon removes over 95% of certain nondegradable organic pollutants, thus making it possible to meet effluent criteria that biological treatment alone could not meet. Specifically, PACT can remove priority pollutants such as benzene, toluene and phenol, plus their chlorinated and nitrated derivatives, and pesticides. It also enhances heavy-metals removal, and removes colors.

As one example, Table V shows the effect of varying amounts of PAC on an organic-chemicals wastewater: Degradable organics (BOD) were adequately removed without PAC, but PAC was needed to remove nondegradable organics (TOC) and color, and to reduce the amount of Cu, Cr and Ni passing through.

PAC may also be needed to prevent certain chemicals from

Table V — Larger doses of powdered activated carbon result in greater removal of organic carbon, color and heavy metals

	Wastewater composition, mg/L							Bioassay,* LC50
	BOD	TOC	TSS	Color	Cu	Cr	Ni	
Influent	320	245	70	5,365	0.41	0.09	0.52	
Biotreatment	3	81	50	3,830	0.36	0.06	0.35	11
+ 50 mg/L PAC	4	68	41	2,900	0.30	0.05	0.31	25
+100 mg/L PAC	3	53	36	1,650	0.18	0.04	0.27	33
+250 mg/L PAC	2	29	34	323	0.07	0.02	0.24	>75
+500 mg/L PAC	2	17	40	125	0.04	<0.02	0.23	>87

* Percentage of wastewater in which 50% of aquatic organisms survive for 48 h.

Table VI — Heavy metals may be precipitated as hydroxides, sulfates or sulfides

Heavy metal	Removal process and constraints	Effluent level, mg/L
Arsenic	Sulfide precipitation; pH 6-7	0.05
	Carbon adsorption; low levels	0.06
Barium	Fe(OH) ₃ coprecipitation	0.05
	BaSO ₄ precipitation	0.5
Cadmium	Cd(OH) ₂ precipitation; pH 10.0	0.1
	Fe(OH) ₃ coprecipitation; pH 8.5	0.05
Copper	Cu(OH) ₂ precipitation; pH 9.0-10.3	0.2
	Fe(OH) ₃ coprecipitation; pH 8.5	0.3
Lead	Pb(OH) ₂ precipitation; pH 10.0	0.5
	Pb(OH) ₃ precipitation; pH 8-9	0.001
Mercury	Fe(OH) ₃ , Al(OH) ₃ coprecipitation; Na ₂ S added	0.1
Nickel	Ni(OH) ₂ precipitation; pH 10.0	0.15
Selenium	Sulfide precipitation; pH 6.5	0.05
Zinc	Zn(OH) ₂ precipitation; pH 8.5	1.0

Source: Ref. 15

process's effluent with granular activated carbon (GAC). Alternatively, activated-sludge biological treatment can be upgraded by adding powdered activated carbon (PAC) to the aeration vessel.

Activated carbon removes organics by adsorbing them onto its microporous surface. The pore size, controlled by the manufacturer, determines the adsorption capability and rate. Most nondegradable organics can be adsorbed; how-

inhibiting biotreatment. In one coke-plant wastewater, 30–50 mg/L of PAC was needed to adsorb chemicals that inhibited nitrification. In an organic-chemicals plant, PAC was added when the temperature fell below 12°C, in order to remove organics that were inhibiting aerobic oxidation.

If PAC usage is high, economics may demand that used PAC be regenerated. At present, wet-air oxidation at 250°C and 750 psig seems the best way to do this.

Ozonation

Certain organic chemicals in wastewaters can be oxidized by ozone (O₃), in the plant or after secondary treatment. The reactions are enhanced by ultraviolet light; and UV may be needed to treat unreactive compounds such as saturated alkanes and halogenated aliphatics.

Ozone is generated by applying a high-voltage electrical discharge to dry air or oxygen; oxygen yields twice as great an ozone concentration (0.5–10 wt%) as does air. In practice, 1 kWh of electrical power produces about 150 g of ozone. Once generated, the ozone/oxygen (or air) mixture is bubbled or diffused into the liquid stream.

Ozone and oxygen react with aromatics and unsaturated aliphatics in water to form organic acids, ketones and alcohols. These can be biodegraded or carbon-adsorbed, and they may react further to CO₂ and H₂O. However, reaction at a pH above 9, in the presence of Fe, Mn and Cu salts, can convert aromatics into phenolics, some of which are toxic.

As for ozone/UV oxidation, it has been effective in treating pesticides as well as hydrocarbon-rich petroleum-processing wastewaters.

Heavy-metals removal

Heavy metals found in wastewaters include arsenic, cadmium, nickel, copper, lead, chromium and so on. If the metal is in inorganic form, it can generally be precipitated as hydroxide by adding lime or caustic soda to the wastewater. However, coprecipitation with Fe(OH)₃ or Al(OH)₃ may be preferred, and certain metals have to be precipitated as sulfides or sulfates, or oxidized or reduced to precipitable forms. Table VI lists typical precipitation results.

Cyanide and ammonia form complexes with many metals, limiting how much of them can be precipitated. Cyanide can be removed by alkaline chlorination or carbon-catalyzed H₂O₂ oxidation, and ammonia by chlorination, ion exchange or stripping. Hexavalent chromium (Cr⁺⁶) must be reduced to the trivalent state (Cr⁺³) before being precipitated by lime. Common reducing agents are ferrous sulfate, sodium metabisulfite and sulfur dioxide.

Batchwise heavy-metal precipitation is preferred for volumes under 30,000–40,000 gal/d, as in a small metal-plating plant. Above that, batch processing requires too much tankage, so continuous processing is preferred.

Alternative methods of heavy-metals removal include:

- Ion exchange, using caustic soda instead of lime to increase resin selectivity.
- Activated-carbon adsorption, which will take up certain heavy-metal ions (e.g., Hg, Cr⁺⁶) as well as organic-complexed metals such as are found in dye wastes.
- Reverse osmosis and evaporation are used to concentrate plating-bath wastes, which then can be recycled.

Phosphorus removal

Excess phosphorus in wastewaters may be removed by anaerobic and aerobic biotreatment in series, but it can also be chemically precipitated, using aluminum, iron or calcium salts:

Using aluminum sulfate (alum), phosphorus can be reduced to 0.3–0.7 mg/L when the Al:P ratio is about 1.5:1 and the pH is between 5.5 and 6.6. Alum acts as a coagulant, so this process can be carried out ahead of the biotreatment clarifier as well as in the plant.

Ferric sulfate is effective also, at Fe:P ratios of 2–5. But the optimal pH is 5, which is too low for biotreatment. At pH 7, iron precipitation can produce a colloid that must be coagulated with polymer. Lime precipitates phosphates as hydroxyapatites, at a pH of 9–10.5.

Table VII — Performance of sludge thickening and dewatering equipment

Equipment, and type of sludge	Loading	Resultant solids content, wt%	Source
Gravity thickener			
Municipal WAS	4-25 lb/ft ² -d	1-3	Ref. 6
Inorganic sludge	25-75 lb/ft ² -d	10-20	Ref. 6
Flotation thickener			
Municipal WAS	3-6 lb/ft ² -h	4-7	Ref. 1
Centrifuge (per unit)			
Paper-mill WAS	60-100 gal/min	11	Ref. 4
Citrus-processing WAS	25 gal/min	9-10	Ref. 2
Vacuum filter			
Municipal WAS	2-8 lb/ft ² -h	10-15	Ref. 18
Belt filter press (per unit of belt width or area)			
Chemical WAS	100-230 lb/ft-h	13-17	Ref. 17
Paper-mill WAS	3-6 m ³ /m-h	12-19	Ref. 13
Paper-mill primary sludge	12-30 m ³ /m-h	18-37	Ref. 13
Meat-processing WAS	3.6 m ³ /m ² -h	17	Ref. 5
Tannery WAS	2.1 m ³ /m ² -h	23	Ref. 5
Pressure filter			
Chemical WAS		20-30	Ref. 16
Chemical WAS	4-h cycle	28	Ref. 11
Citrus-processing WAS	2-h cycle	27	Ref. 2
Tannery WAS	0.09 m ³ /m ² -h	48	Ref. 5

WAS = Waste activated sludge

Filtration

Filters are used to pretreat low-solids wastewaters, to remove precipitates, and to remove solids carried over from biological treatment. Sand, gravel and other particles are used as filter media. The filters are otherwise classified by the direction of flow (up or down), the driving force (gravity or pressure), the bed homogeneity (single-, dual- or multimedia), and the filtration depth (surface or deep-bed). In general, filters are 2–5 ft deep, and use media of 0.25–2 mm. They can handle 2–5 gal/ft²-min, and yield effluents having less than 5–10 mg/L TSS and less than 3–7 mg/L BOD.

Dual- or multimedia filters are preferred for polishing effluents from biological treatment because the gelatinous

solids could block the surface of a fine-sand filter. A typical dual-media filter uses 0.5 m of 1-mm anthracite coal above 0.3 m of 0.45-mm sand. The coal intercepts larger particles, thereby extending the capacity of the sand. Typical loadings are 4-8 gal/ft²-min. After a cycle of 6-12 h, the filter is scoured with air, and backwashed with air and water, to remove accumulated solids.

Upflow sand filters, with layers of graded gravel and coarse sand, can be backwashed with raw water, which is an advantage. Surface sand filters with gravity downflow have shorter cycles, but use less backwash water. They are preferred for fragile chemical floes.

Recent advances include moving-bed filters in which the top layer of the medium is continuously removed, and continuously-backwashed deep-bed filters, such as the DynaSand filter (Parkson Corp.), which can handle up to 10 gal/ft²-min.

Sludge thickening and dewatering

Waste solids in slurry form are produced by primary sedimentation, secondary clarification, and various inplant treatments and pretreatments. These sludges typically have to be thickened and dewatered before they can be landfilled, incinerated or otherwise disposed of. Certain sludges may also be anaerobically digested, heat-treated or oxidized, to reduce their mass or to make them easier to dispose of. Fig. 1 includes a generic flowsheet for sludge treatment. Specific choices depend on such factors as how much water can be removed mechanically, and whether the dewatered sludge can support combustion.

Sludges from sedimentation or clarification are generally slurries of only 0.5-6% solids content. Thickening ups the solids to 2-20%, and mechanical dewatering yields cakes having 15-50% solids. To go beyond this usually requires drying, which is expensive. In general, gelatinous slurries such as waste activated sludge yield lower solids contents than do primary and inorganic-chemical sludges.

Sludges are thickened either by gravity or by dissolved-air flotation. A gravity thickener is a tank equipped with a rotating rake that breaks up bridged particles and so speeds settling. Inorganic sludges can be thickened to 20% solids, at 75 lb/d per ft² of surface; waste activated sludge can be thickened to 2.5% solids, at 4-25 lb/ft²-d.

Dissolved-air flotation can thicken activated sludge to 4-6%. Here, air is injected into recycle water (100-250% of feed) pressurized to 50-70 psig. In the thickener, the pressure is lowered, releasing bubbles that attach to sludge particles and float them up.

Centrifugation at 1,000 gravities or more can thicken and dewater sludges to 5-35% solids. Since basket centrifuges have to be emptied batchwise, solid-bowl and disc-nozzle centrifuges that discharge solids continuously are more suitable for separating large volumes of sludge.

Filtration captures more of the solids than does centrifugation, and generally produces a drier cake. In vacuum filtration, a drum covered with porous cloth or steel mesh picks up slurry as it rotates through a tank. A vacuum pulls the water through the filter medium, leaving a cake of 15-40% solids to be scraped off. In a filter press, batchwise filtration yields 20-45% solids.

Continuous belt filter-presses are used for difficult-to-dewater sludges such as waste activated sludge, which they can dewater to about 15-20% sol-

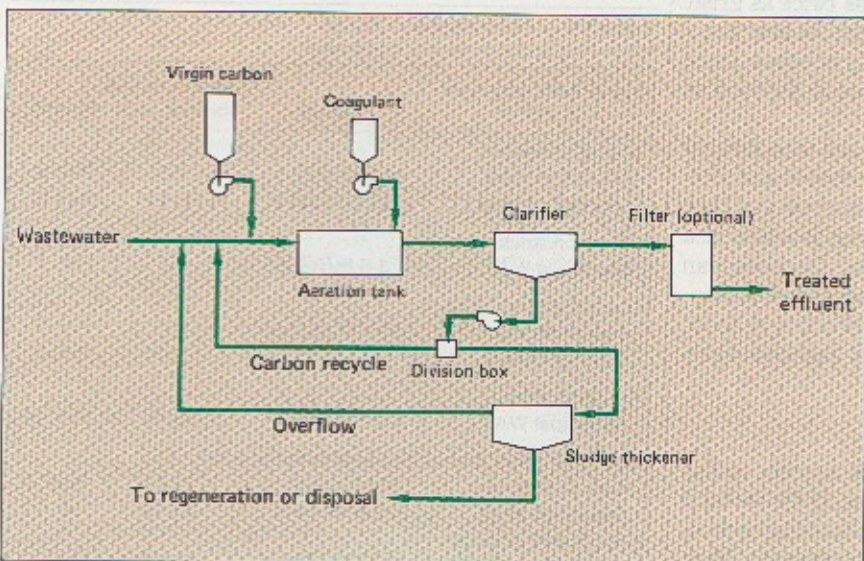


Figure 13 — In the PACT process, powdered activated carbon (PAC) adsorbs organics present in the activated-sludge aeration tank

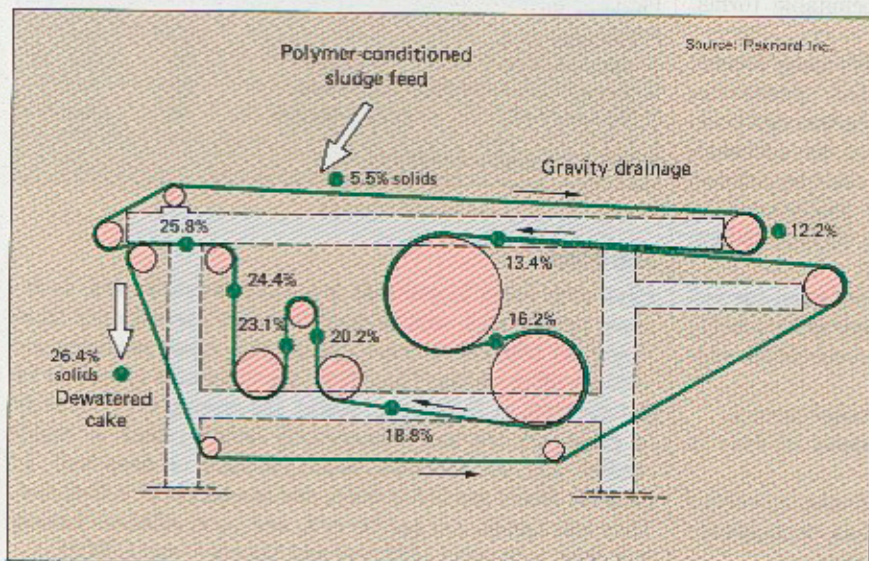


Figure 14 — A belt filter press progressively squeezes the water out of waste activated sludge

ids, while capturing 90–95% of the total solids. Primary sludges they can dewater to 15–40% solids. Fig. 14 illustrates how water is progressively squeezed out of a sludge in such a press. Table VII offers some examples of thickening and dewatering performance.

Still, many biological sludges are difficult to dewater, requiring excessive dosages of coagulants. One way around this is to heat the sludge under pressure for a short time. This coagulates the solids, breaks down any gels, and generally makes it possible to dewater the sludge without chemical coagulation. It also sterilizes and deodorizes the sludge.

Sludge that is to be disposed of on land or in a lagoon can be made relatively inert by aerobic or anaerobic digestion. Aerobic digestion is preferred; here, 10–20 d of aeration removes 90% of the degradable organics in the sludge.

Sludge disposal

Wet sludges can be disposed of by lagooning or by spreading or spraying them over land (landfarming), but if they contain heavy metals or other priority pollutants they may be considered hazardous wastes, and thus require special disposal. Sludges can also be incinerated; the amount of fuel needed for this depends on their dryness and energy content.

Sludges often are lagooned, but organic ones should first be aerobically or anaerobically digested, to eliminate odor. A lagoon may be operated as a drying bed, with periodic solids removal, or as a permanent lagoon, in which case the site is closed up once the lagoon is full of solids.

Digested biological sludges have some fertilizer value, and clean ones can be disposed of at loadings of 100–300 dry tons per acre. Waste activated sludge can be disposed of in algae-filled lagoons, in which anaerobic digestion occurs on the bottom and aerobic digestion on the top.

Incineration requires drying, to remove moisture, and combustion of some fuel, to bring the sludge and its volatiles to their ignition point. After this, the sludge may burn by itself if it has enough energy. Thermal values range from 6,500 Btu/lb (dry basis) for waste activated sludge to 17,000 Btu/lb for oily sludge.

In a multiple-hearth incinerator, moisture is driven off at the top by exhaust gases (600°F) which are then scrubbed. In the center hearths, volatile gases and solids are burned. At the bottom (1,000°F), fixed carbon is burned. A fluidized-bed incinerator, in contrast, operates at 1,400–1,500°F, resulting in faster and more thorough drying and combustion.

Cost-effective wastewater treatment

Having covered the principal means of treating wastewaters, let us now consider how to find the most economical means of obtaining the desired effluent quality:

1. Characterize the wastewater. It is essential to know the composition, concentration and flowrate of the various waste streams, and to understand how and why the streams are generated. In an operating plant, the wastewaters are available for examination. As for a new plant, data for similar plants may be available within the company or in the literature. It is also important to know how the quality or quantity of the wastewaters is expected to change in the future.

Some treatability testing may be needed, especially in a plant that already has a biological-treatment facility but is

confronted with new wastes. For instance, at a large chemicals complex, wastewaters are screened for treatability as follows: The stream is pretreated to remove heavy metals and suspended solids, if any, and its pH is adjusted. It is then fed to a batch activated-sludge reactor, primed with biomass from the plant's treatment facility. If the wastewater is quickly degraded, as it should be, it can be fed into the plant's main flow. If not, the choices are in-plant pretreatment, PAC addition to the bioreactor, or GAC treatment of the effluent.

2. Decide on an overall treatment scheme. Certain streams may be combined into a large flow and treated in a central onsite facility, but others are best treated individually. This is the case for streams containing wastes that would be very expensive to remove from a large, combined flow, and for fairly clean streams that can be reused in the plant after a minimal amount of treatment. It may also be possible to

Table VIII — Net-present-value analysis summarizes 20-year costs of alternative wastewater-treatment facilities

Treatment process	Net present value, \$ millions	
	1 million gal/d	10 million gal/d
Physical and chemical treatment	- 6.46	-19.4
With GAC adsorption	-13.1	-45.5
Activated-sludge treatment	- 4.25	-17.5
With solids handling	- 9.04	-24.9
With solids handling and two-stage nitrogen removal	-10.4	-31.4
Rotating biological contactor, with solids handling	- 8.55	-21.3
PACT, with solids handling and carbon regeneration	N.A.	-28.9

Basis: 1980 costs, 20-year term, 9% discount rate, BOD loading of 250 mg/L.
Source: D.L. Ford, personal communication.

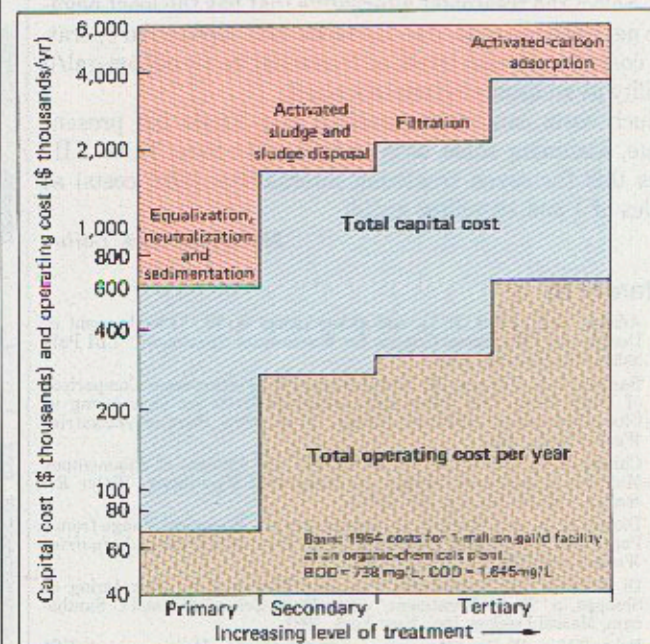


Figure 15 — Capital and operating costs for a 1-million-gal/d organic-chemicals wastewater-treatment facility

sewer certain streams to a publicly owned treatment works, after some level of onsite pretreatment. In this case, there is a tradeoff between the cost of onsite treatment and the POTW's effluent surcharges.

3. Select a sequence of treatment processes. Onsite treatment and pretreatment must be able to meet the effluent criteria in an economical manner. Since one process often feeds into another, it is generally necessary to consider all of them together, and to compare alternative sequences. For each process alternative, factors such as reliability, flexibility, and byproduct value should also be considered.

4. Determine design sizes. Generally, hydraulic structures and most processing systems are designed for the 90th percentile of wastewater flow; large basins are sized for the average flow. Of course, if the flow is expected to increase or decrease in the future, this should be considered up front.

5. Estimate the capital cost. Equipment costs are available in the literature, and from vendors. These can be translated into capital costs by adding the costs of instrumentation, engineering and construction, utilities, land, laboratories and offices, and contingencies.

Capital costs can also be estimated by rule-of-thumb comparison to identical facilities elsewhere. In general, capital cost varies with about the 0.6 power of capacity (0.5-0.7), so a 2-million-gal/d plant should cost about 1.52 ($2^{0.6}$) times as much as a 1-million-gal/d plant of the same design. There is no rule of thumb for capital vs. concentration; however, D. L. Ford reports that the cost of a 10-million-gal/d activated-sludge system (without solids handling) doubles as the BOD is quadrupled from 250 mg/L to 1,000.

6. Estimate the operating and maintenance cost. This includes labor, chemicals and other inputs (e.g., GAC), fuel, power, transportation of sludge, plus maintenance. There is less economy of scale for operation and maintenance; the rule of thumb is that it varies as the 0.85 power of capacity.

7. Select the treatment alternative that has the least negative net present value. Fig. 15 shows 1984 capital and operating costs for several levels of treatment in a 1-million-gal/d facility at an organic-chemicals plant.

Such costs can be summarized in a single net present value, assuming some term and discount rate. Table VIII does this for seven treatment alternatives (1980 costs) at scales of 1 and 10 million gal/d.

Mark Lipowicz, Editor

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