CHAPTER 8

Removal of Organic Dissolved Solids

In earlier years, the removal of dissolved organic matter was primarily based on its oxygen-demanding characteristics. During the latter part of the twentieth century, the emphasis for its removal began to be based on its hazardous component. Unfortunately, the treatments for the two components—oxygen-demand and hazardous—are not compatible. The first is removed largely by biological means (as you will read in this chapter), and the second must usually be segregated and treated by sophisticated and often innovative techniques. The treatment of specific organic hazardous (or toxic) matter is presented in Chapter 11.

The removal of dissolved organic matter from wastewaters is one of the most important tasks of the waste engineer, and, unfortunately, one of the most difficult. These solids are usually oxidized rapidly by microorganisms in the receiving stream, resulting in loss of dissolved oxygen and the accompanying ill effects of deoxygenated water. They are difficult to remove because of the extensive detention time required in biological processes and the elaborate and often expensive equipment required for other methods. In general, biological methods have proved most effective for this phase of waste treatment because bacteria are adept at devouring organic matter in wastes, and the greater the bacterial efficiency the greater the reduction of dissolved organic matter. Microorganisms, however, are quite “temperamental” and sensitive to changes in environmental conditions, such as temperature, pH, oxygen tension (level of oxygen concentration), mixing, toxic elements or compounds, and character and quantity of food (organic matter) in the surrounding medium. It is the responsibility of the engineer to provide optimal environmental conditions for the proliferation of the particular biological species desired.

There are many varieties of biological treatment, each adapted to certain types of wastewaters and local environmental conditions such as temperature and soil type. Some specific processes for treating organic matter are: (1) lagooning in oxidation ponds; (2) activated-sludge treatment; (3) modified aeration; (4) dispersed-growth aeration; (5) contact stabilization; (6) high-rate aerobic treatment (total oxidation); (7) trickling filtration; (8) spray irrigation; (9) wet combustion; (10) anaerobic digestion;

(11) mechanical aeration system; (12) deep-well injection; (13) foam phase separation; (14) brush aeration; (15) subsurface disposal; and (16) the Bio-Disc system.

Lagooning

Lagooning in oxidation ponds is a common means of both removing and oxidizing organic matter and wastewaters. More research is needed on this method of treatment, which originally was developed as an inexpensive procedure for ridding industry of its waste problem. An area adjacent to a plant was excavated, and wastewaters either flowed or were pumped into the excavation at one end and out into a receiving stream at the other end. The depth of the lagoon depended on how much land was available, the storage period desired or required, and the condition of the receiving stream. Little attention was paid originally to the effect of depth on bacterial efficiency. In fact, reduction of dissolved organic matter was usually not anticipated or even desired, because it was presumed, and with good reason, that biological degradation of organic matter would lead to oxygen depletion and accompanying nuisances from odors. Thus, the lagoons served solely to settle sludge and equalize the flow. Modern techniques, however, have led to new theories about the stabilization of organic matter in lagoons.

We now know that stabilization or oxidation of waste in ponds is the result of several natural self-purification phenomena. The first phase is sedimentation. Settleable solids are deposited in an area around inlets to the ponds, the size of the area depending on the manner of feeding in the waste and location of the inlet. Some suspended and colloidal matter is precipitated by the action of soluble salts; decomposition of the resulting sediment by microorganisms changes the sludge into inert residues and soluble organic substances, which in turn are required by other microorganisms and algae for their metabolic processes.

Decomposition of organic material is the work of microorganisms, either aerobic (living in the presence of free oxygen) or anaerobic (living in absence of free oxygen). In a pond in which the pollution load is exceedingly high or which is deep enough to be void of oxygen near the bottom, both types of microorganism may be actively decomposing organic material at the same time. A third type of microorganism, the facultative anaerobic, is capable of growth under either aerobic or anaerobic conditions and aids in decomposing waste in the transition zone between aerobic and anaerobic conditions. It is desirable to maintain aerobic conditions, because aerobic microorganisms cause the most complete oxidation of organic matter. Anaerobic bacteria have been most effective in oxidizing dairy, textile, and other highly soluble organic wastes.

Table 8.1 gives a general scheme of the microbial degradation of the organic constituents in sewage. It also points out the difference between aerobic and anaerobic decomposition.

Algae are significant in stabilization ponds in that they complete nature's balanced plant–animal cycle. Whether seasonal or perennial, algae utilize CO_2 sulfates, nitrates, phosphates, water, and sunlight to synthesize their own organic cellular material and give off free oxygen as a waste product. This oxygen, dissolved in pond water, is available to bacteria and other microbes for their metabolic processes, which include

TABLE 8.1
Biological Degradation of Organic Constituents in Sewage

		End-Products	
Substance Decomposing	*Class of Microbial Enzymes*	*Anaerobic Decomposition*	*Aerobic Decomposition*
Proteins	Proteinase[a]	Amino acids Ammonia Hydrogen sulfide Methane Carbon dioxide Hydrogen Alcohols Organic acids Phenols Indols	Ammonia, nitrites, nitrates Hydrogen sulfide, sulfuric acid Alcohols Organic acids Carbon dioxide Water
Carbohydrates	Carbohydrase[a]	Carbon dioxide Hydrogen Alcohols Fatty acids	Alcohols Fatty acids Carbon dioxide Water
Lipids (fats)	Lipase[a]	Fatty acids Carbon dioxide Hydrogen Alcohols	Fatty acids and glycerol Alcohols Carbon dioxide Water

[a] Class of enzymes only. Dozens of enzymes may be utilized in this degradation.

respiration and degradation of organic material in the pond. Thus, we have a completed cycle in which (a) microorganisms use oxygen dissolved in the water and (b) break down organic waste materials to produce (c) waste products such as CO_2, H_2O, nitrates, sulfates, and phosphates, which (d) algae use as raw materials in photosynthesis, thereby (e) replenishing the depleted oxygen supply and keeping conditions aerobic so that the microorganisms can function at top efficiency (Figure 8.1). However, one drawback of algae should be mentioned, namely, that when they die, they impose a secondary organic loading on the pond. Another disadvantage is a seasonal one: Algae are less effective in winter.

Ice and snow cover during winter months interferes with the stabilization process in the following manner:

1. It prevents sunlight from penetrating the pond, causing a reduction in the size and number of algae present. Algae are not necessarily killed by the absence of sunlight (those known as *facultative chemo-organotrophs* can carry on metabolic processes despite darkness), but they release little or no oxygen without sunlight.
2. It prevents mixing and re-aeration by wind action.
3. It prevents re-aeration by atmosphere–water dynamic equilibrium phenomena.
4. It usually results in anaerobic conditions if it continues over an extended period.

These factors tend to result in a lowered pond or lagoon efficiency during the winter.

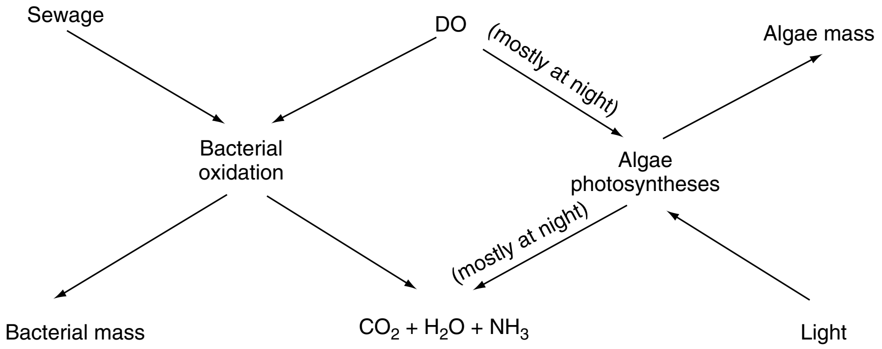

FIGURE 8.1. The role of algae in stabilization ponds (adapted from North and South Dakota Departments of Health and the U.S. Department of Health, Education and Welfare 1957).

Hermann and Gloyna (1958) (disregarding the part played by minerals) describe the reaction in high-rate ponds in which sewage is oxidizing as

$$C_{11}H_{29}O_7N + 14O_2 + H^+ \rightarrow 11CO_2 + 13H_2O + NH_{4+}.$$

The canning industry, one of the first to attempt lagooning, soon found it difficult to maintain aerobic conditions in basins; other industries experienced similar situations. As industries became aware that biological degradation occurs in lagoons, they made attempts to encourage and control the oxidation and began to refer to such lagoons as *waste-oxidation basins*.

Most modern oxidation basins have a maximum water depth of 4 feet and operate on a continuous-flow basis. Engineers try to maintain in the basin near-neutral pH, adequate oxygen concentration, and sufficient nutrient minerals for biological oxidation. Chemical neutralizers are used to alter pH values, oxygen concentrations are maintained by reducing detention times and using shallow basins, and mineral-salts nutrients may be added as needed, to accelerate biological activity. Biochemical oxygen demand (BOD) removals range from as low as 10% to as high as 60–90%.

In an interesting full-scale study, Nemerow and Bryson (1960) treated an airbase oxidation pond, at 43° north latitude with ice cover during the winter, with an elevated loading of 130 pounds of BOD in the wastewater per acre of pond area. The BOD reductions at these relatively high loadings ranged from 87.7% in August to 53% in January, with a yearly average of 69.3%. In another pilot-plant study, Nemerow (1960) achieved BOD removals in excess of 80%, using close-baffled 4-ft-deep or unbaffled 8-ft-deep basins during the critical summer period in central New York State, at elevated loadings of 312–467 lb/acre/day. A photograph of the five parallel pilot-plant basins is shown in Figure 8.2.

Oswald (1960) believes that in such heavily loaded ponds, particularly during periods when methane fermentation is either nonexistent or limited by temperature and when algal photosynthesis is not taking place in the surface layers, buildup of organic

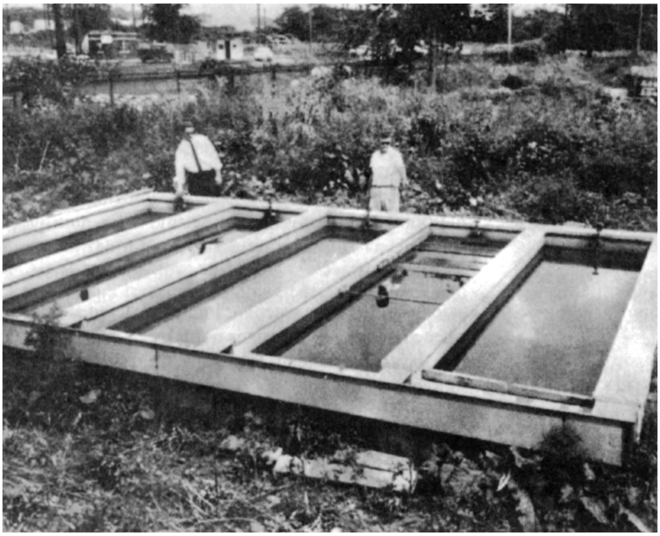

FIGURE 8.2. Accelerated-oxidation pilot-plant basins (adapted from Nemerow 1960). Used with permission from John Wiley and Sons.

acid occurs, with a subsequent lowering of the pH level and emission of hydrogen sulfide from the pond. The author, however, did not experience these odors, even at the high loadings described earlier. Oswald (1960) offered the explanation that if methane fermentation becomes established in the bottom deposits, high rates of BOD removal may be attained without appreciable odors. He also believed that ponds in which both photosynthesis oxygenation and methane fermentation occur (facultative ponds) must be restricted to about 50 lb of BOD per acre per day, because conditions are at times unfavorable for either process. The author does not necessarily agree with these findings. Furthermore, Oswald's later high-rate oxidation ponds for treating sewage in warmer climates have been loaded to more than 600 lb of BOD per acre per day or more, being aerated for an hour each midnight. When lagooning organic wastes—which must be prevented from reaching the groundwater as well as surface bodies of water—preventative measures must be taken. These methods include making the bottom and sides of lagoons impermeable to the lagoon contents, whether or not they are partially decomposed. Banerjee (1997) gives a list of liner materials commonly used (Table 8.2).

The reader is referred to the discussion in Chapter 7 of the necessity of preventing algae growth in bodies of water that are used for water supplies and recreational activities.

Activated-Sludge Treatment

The activated-sludge process has proved quite effective in the treatment of domestic sewage as well as a few industrial wastes from large plants. In this process, biologically active growths are created, which are able to adsorb organic matter from the wastes and convert it by oxidation-enzyme systems to simple end-products like CO_2, H_2O, NO_3,

TABLE 8.2
Materials Potentially Useful for Liners of Ponds Containing Hazardous Wastes

- Compacted native fine-grain soils
- Bentonite and other clay sealments
- Asphaltic compositions
  - Asphalt concrete
  - Hydraulic asphalt concrete
  - Preformed asphalt panels
  - Catalytically blown asphalt sprayed on soil
  - Emulsified asphalt sprayed on soil or on fabric matting
  - Soil asphalt
  - Asphaltic seals
- Portland cement compositions
  - Concrete, with seal coats
  - Soil cement, with and without seal coats
- Soil sealants
  - Chemical
  - Lime
  - Penetrating polymeric emulsions and latexes
- Sprayable liquid rubbers
  - Polyurethanes
  - Polymeric latexes
- Synthetic polymeric membranes—reinforced and unreinforced
  - Butyl rubber
  - Ethylene propylene rubber (EPDM)
  - Chlorosulfonated polyethylene (Hypalon)
- Chlorinated polyethylene (CPE)—elasticized polyolefin (3110)
- Polybutylene (PB)
  - Polychloroprene (Neoprene)
  - Polyester elastomers
  - Polyethylene (PE)
  - Polyvinyl chloride (PVC)

Adapted from Banerjee (1997).

and SO_4. Biological slimes develop naturally in aerated organic wastes, which contain a considerable portion of matter in the colloidal and suspended state, but for the efficient removal of organic dissolved solids, there must be high floc concentrations to provide ample contact surface for accelerated biological activities. The flocs (zoogleal masses) are living masses of organisms, food, and slime material, and are highly active centers of biological life; hence, the term "activated sludge." They require food, oxygen, and living organisms in a delicately controlled environment.

Various degrees of efficiency are obtained by controlling the contact period and/or the concentration of active floc. The contact period can be regulated by careful design of the hydraulic systems of aeration basins, the average time of aeration being 6 hours for domestic sewage and 6–24 hours for various industrial wastes. The desired concentration of active floc is maintained by recirculating a specific volume of secondary settled sludge, normally about 20%. Higher sludge quantities lead to greater BOD removal and create a need for more air and food (organic matter) for proper balance. Also, "old" heavy sludge tends to become mineralized and devoid of oxygen, which results in a less active floc. The reverse is true of a "young" light sludge floc. The "age" of the growths, therefore, becomes an important consideration.

Busch and Kalinske (1956) summarize the situation by saying that for optimal activity, the kinetics of activated sludge require the following: a young flocculent sludge in the logarithmic stage of growth; maintenance of the logarithmic growth state by controlled sludge wastage; continuous loading of the organisms; and elimination of anaerobic conditions at any point in the oxidative treatment.

Hazeltine (1956) has said of the present status of domestic-sewage activated-sludge treatment that BOD removals are usually more than 90% when the loadings are less than 0.3 lb of BOD per pound of suspended solids in the water under aeration. Efficiencies are difficult to predict when these loadings are increased to 0.5 lb/lb. Normally, the BOD loading is related to the aeration-tank capacity; about 30–35 pounds of BOD per 1,000 ft^3 can be treated in plants with about 2,000 ppm of suspended solids under aeration.

Sawyer (1960) lists the limitations of the domestic-sewage activated-sludge process as follows: BOD loadings are limited to about 35 lb/1,000 ft^3 of tank capacity, thus requiring relatively long detention time and resulting high capital investment; there is a high initial oxygen demand by the mixed liquors; there is a tendency to produce bulking sludge; the process cannot produce an intermediate quality of effluent; high sludge/recirculation ratios are required for high BOD wastes; there are high solids loadings on final clarifiers; and large air requirements accompany the process.

The Kraus process (1945) attempts to overcome some of the sludge-bulking problems of conventional activated-sludge plants by controlling the "sludge volume index" (a measure of the volume occupied by one gram of suspended solid). The process is similar to that of conventional activated-sludge treatment, employing separate re-aeration for sludge, except that some digester sludge, digester supernatant, and activated sludge are aerated together for as much as 24 hours, in what he terms a *nitrifying aeration tank*. BOD loadings as high as 170 lb/1,000 ft^3/day have been used, with removals near 90% (Kraus 1955).

Von der Emde (1960) notes that ciliated and flagellated protozoa, as well as bacteria, are normally prevalent in activated sludge. When the BOD loading is high or very low, flagellates replace the ciliates, regardless of the level of oxygen present. Where there are short aeration periods, or when only traces of oxygen are maintained, bacteria are observed only in the sludge.

Many characteristics of industrial wastes (e.g., toxic metals, lack of nutrients required for biological oxidation, organic nondegradable matter, high temperature, and high or low pH values) give rise to problems requiring careful analysis. When the suitability of this process for a particular industrial waste is in question, laboratory and/or filed pilot plant will yield the results necessary for decision making.

Heukelekian (1949a) believed that bulking of activated sludge should result when conditions are not so unfavorable that they destroy the purification mechanism and yet sufficiently unfavorable that they bring a shift in the delicate biological balance. One of these unfavorable conditions should be an inadequate oxygen supply. If the oxygen supply in relation to the demand becomes inadequate, *Sphaeroltilus* and other filamentous organisms attain the ascendancy and the sludge becomes bulking. Biochemical activities of these organisms would bring about the purification in a way similar to the desirable sludge organisms except with lower and more efficient oxygen utilization at the lower tensions. In other words, when the sludge is diffuse and filamentous, it exposes more surface, which might enable the sludge to obtain the limited amount of oxygen present in the medium immediately surrounding it. This type of sludge, however, usually produces a sparkling effluent. Dairy wastes exhibit this problem, which has been overcome by the addition of ammonium chloride to provide a more favorable carbon-to-nitrogen ratio.

Modified Aeration

Modified, tapered, and step aeration are variations of the activated-sludge treatment. The objective is to supply the maximum of air to the sludge when it is in the optimal condition (sludge age) to oxidize adsorbed organic matter. The location of the aerator and the quantity of air supplied vary, depending on sludge solids and organic matter to be oxidized. Lower volumes of air and shorter detention times are claimed for these processes, while the mechanisms and theories of operation are similar to those of activated sludge.

Step aeration attempts to eliminate the problems encountered with plain aeration by providing 2 to 3 hours of aeration only. Highly activated and concentrated sludge floc is returned to the aeration tank at the proper location (usually the inlet); this reduces bacterial lag, accelerates logarithmic bacterial growth, and provides abundant surfaces for adsorption of new cells. The chief advantage to this process is the flexibility it offers the operator. Figure 8.3 shows that one can obtain almost any desired ratio of primary effluent to sludge seed returned.

Dispersed-Growth Aeration

Dispersed-growth aeration is a process for oxidizing dissolved organic matter in the absence of flocculent growths (Heukelekian 1949a). The bacteria (seed) for oxidizing are present in the supernatant liquor after wastes have been aerated and settled. A portion of this supernatant liquor is retained for seeding incoming wastes, whereas the settled

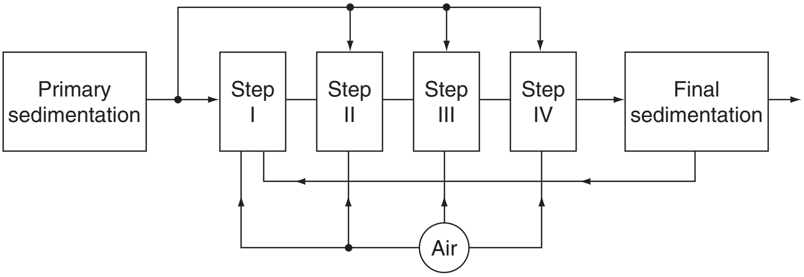

FIGURE 8.3. Schematic diagram of step-aeration treatment. Step I, high sludge seed (4,000 ppm); step II, 2,000 ppm; step III, 1,000 ppm; step IV, 800 ppm.

sludge from the secondary settling tank is digested or treated by other sludge-treatment methods. This process has been successfully used to treat many types of dissolved organic wastes (Heukelekian 1949c; Nemerow 1954, 1955, 1956, 1957). Its advantage is that it eliminates certain problems associated with sludge seeding. With many industrial wastes, it is difficult to build up any significant sludge concentration; in such cases, dispersed growth aeration (which is not dependent on sludge) finds ready acceptance. Dispersed-growth aeration does require more air to achieve the same BOD reduction as the activated-sludge process. However, when one considers that the initial BOD in dispersed-growth aeration is usually quite high, the amount of air required per pound of BOD removed is about the same as that used in the activated-sludge process, even though aeration periods to reach the same BOD reduction are normally quite lengthy (24 hours as compared to 6). Treatment by dispersed-growth aeration involves complete removal by oxidation, as in activated-sludge treatment.

Heukelekian (1949a) originally conceived this idea of seeding concentrated soluble organic wastes with dispersed, instead of flocculent, growths, when he discovered that bacteria in culture mediums normally grow in the dispersed state or in small groups and that seeding is essential for high-rate biological activity. If a waste contains only soluble material, no flocculent growth should form. In his early work on penicillin and streptomycin wastes (Heukelekian 1949b,c), he made the following claims for the dispersed-growth aeration process:

1. It is better adapted than activated-sludge methods for the treatment of concentrated soluble organic wastes because (a) activated sludge has a tendency to bulk with concentrated organic wastes, and (b) it is difficult to develop an activated sludge from a soluble waste.
2. Little sludge is formed with dispersed growths when soluble substrates are decomposed.
3. The percentage of BOD reduction decreases as the strengths of penicillin and streptomycin wastes are increased, but 80% reduction may be expected with wastes up to 3,000 ppm of BOD. Greater BOD reductions are possible when the BOD is less than 1,000 ppm and the waste is aerated for 24 hours.
4. The effluent has a higher turbidity than the raw water, and color is not removed.
5. The process may be used as a pretreatment unit for conventional biological treatment processes.
6. The seed material can readily be developed and adapted from soil or sewage within a few days.
7. Optimum results are obtained with air rates of 2–3 ft^3/gallon/hr; stronger wastes require higher air rates.
8. The initial pH of the waste does not seem a critical factor, because the pH increases during aeration. The BOD of raw waste with a pH of 6.4 is reduced as much as the BOD of the same waste adjusted to 7.2.

Nemerow and Rudolfs (1952) also found this method of treatment suitable for rag and jute paper-mill wastes. In a basic study of the oxidation of glucose by dispersed-growth aeration, Nemerow and Ray (1956) found 5 million bacteria per milliliter when using nutrient broth as a medium. The two major types of bacteria found during the 24-hour aeration period were

1. Dispersed, short, thick, round-ended rods; approximate size, 2–2.5 microns × 1 micron. Some of these organisms appeared as fingerlike capsules. As the aeration period progressed, there was an apparent increase in the number of slime-enmeshed bacteria (Figure 8.4).
2. *Sphaeroltilus*-like organisms, often as unsheathed forms (Figure 8.5); these were more abundant after 6 hours of aeration and reached an apparent maximum after 24 hours.

In studying the suitability of dispersed-growth aeration for industrial wastes containing both proteins and carbohydrates, Struzeski and Nemerow (1957) found such wastes amenable to oxidation by this process. Biological oxidation was enhanced by an increase in temperature, as shown in Figure 8.6, and initial pH values up to 9.5 did not hamper it. It was also found that when soluble protein-carbohydrate wastes are to be treated by dispersed-growth aeration, units must be designed to allow ample detention time, because air rates above the critical level (1,050 ft^3 of air per pound of BOD per day) do not increase the reduction of BOD.

Contact Stabilization

Biosorption is the commercial name of one equipment manufacturer's high-rate biological oxidation process, used mainly for domestic sewage. It was originally

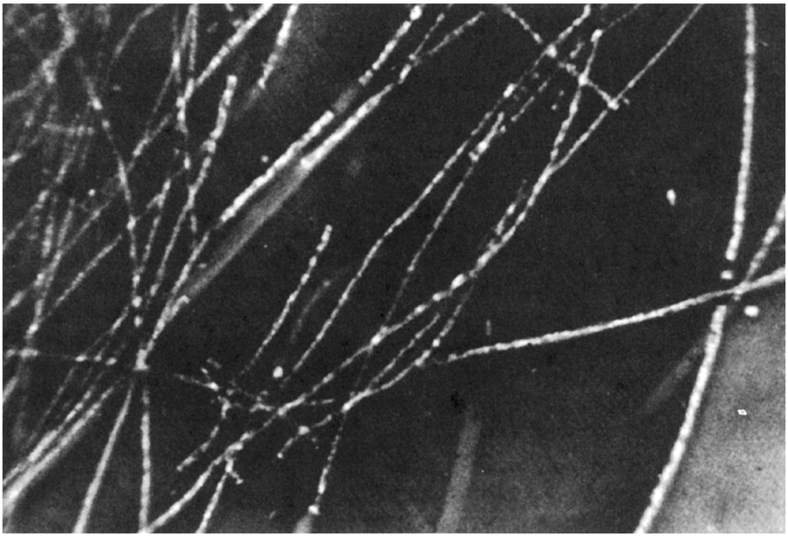

FIGURE 8.4. *Sphaerotilus*-like organism, sheathed and unsheathed (×620). Used with permission from John Wiley and Sons.

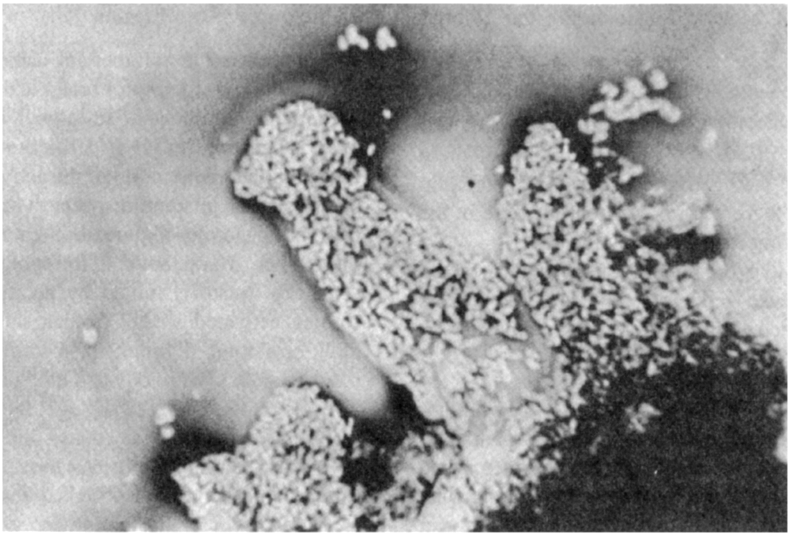

FIGURE 8.5. Round-ended rods in a capsule of slime (×620). Used with permission from John Wiley and Sons.

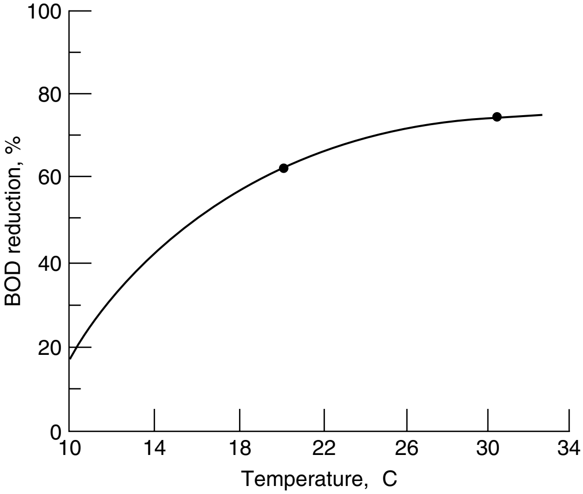

FIGURE 8.6. Effect of temperature on average BOD reduction of a synthetic protein–glucose waste, using a dispersed-growth aeration system, after 24 hours of aeration and no settling.

developed at Austin, Texas by Ullrich and Smith (1951). It is essentially a modification of the activated-sludge process and is similar in some respects to the step-aeration process but generally requires less air and plant space. In the contact-stabilization process, raw waste is mixed by aeration with previously formed activated sludge from a stabilization-oxidation tank, or aerobic digester, for a short

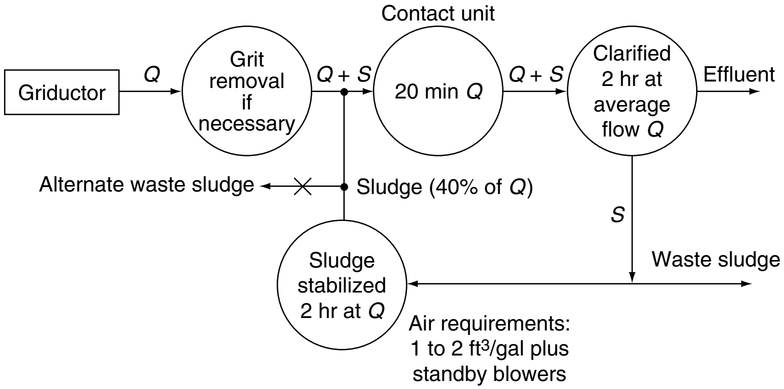

FIGURE 8.7. Schematic arrangement of contact-stabilization process.

period (15–20 minutes). This activated-sludge–raw-waste mixture is then clarified by settling for about 2 hours, after which the settled sludge (consisting of activated-sludge floc with adsorbed impurities from the raw waste) goes through intense biological oxidation in the stabilization-oxidation basin for an aeration period of 1–2 hours. It then returns to the mixing tank and is again mixed with raw waste so that it can absorb and adsorb added organic matter, and so on, in a continuous process. Excess, or waste sludge, can be taken from the system after either the clarifying or the stabilizing step, for anaerobic digestion or for dewatering on vacuum filters (Figure 8.7).

Ullrich and Smith (1951, 1957) claimed that this process requires less aeration-tank capacity than other processes, because the real aeration or reactivation takes place in the settled and concentrated sludge, not in the mixed liquor. Because the sewage and returned sludge is given only a brief mix, a small mixing compartment is needed. Pertinent pilot-plant and full-scale operating results are given in Table 8.3.

High-Rate Aerobic Treatment

High-rate aerobic treatment (total oxidation) has used since the 1950s to oxidize organic wastes (Tyre et al. 1991). This process consists of comminution of the waste, long-period aeration (1–3 days), final settling of the sludge, and return of the settled sludge to the aeration tank. There is no need for primary settling or sludge digestion, but the aeration system must be large enough to provide the required aeration period. The total-oxidation process is particularly useful in small installations, because it does not require a great deal of supervision. Little difficulty occurs with bulking on the sludge, even though the settling period is relatively short at times. In fact, because the solids resulting from this process are mostly of low volatility and therefore high in ash, the settling rate is quite fast. Return of the sludge is continous and very rapid in comparison with normal activated-sludge practice. By returning sludge at a high rate

(100–300% of flow), the system is kept completely aerobic at all times. The concentration of solids in the mixed liquor after a long period reaches a high level, and a portion of the sludge can then be wasted to reduce the concentration to 3,000–5,000 ppm. Lesperance (1965) suggests that a waste sludge can be expected equal to 0.15 lb per pound of BOD removed. The small volume of wasted sludge is then stored and further concentrated until removed by a tank car or other means to an area away from the plant.

Although it produces little waste sludge, the high-rate aerobic treatment has the disadvantages of requiring about three times as much air as conventional activated-sludge plants and of releasing some floc in the effluent. On the other hand, it needs very little operational maintenance and is well suited for shock loadings from industrial operations.

Another version of this treatment is referred to as a "completely mixed system" (McKinney et al. 1958). It operates on the assumption that if microorganisms are kept in a constant state of growth, they operate at maximum efficiency and are adapted to the particular character and concentration of the waste. This constant-growth state can be maintained only if: (1) the microorganisms and raw wastes are thoroughly and continuously mixed; (2) the organic concentration is held constant; and (3) the effluent is separated form the microorganisms at a constant rate that is equal to the waste-feed rate. Figure 8.8 depicts a typical complete-mixing activated-sludge system (McKinney et al. 1958). A loading of 60 lb of oxidizable organics per 1,000 ft^3 of aeration tank is possible with this type of treatment.

Trickling Filtration

"Trickling filtration" is a process by which biological units are coated with slime growths (zoogleal forms) from the bacteria in the wastes. These growths adsorb and oxidize dissolved and colloidal organic matter from the wastes applied to them. When the rate of application is excessive (10–30 million gallons/acre/day [mgad]) and

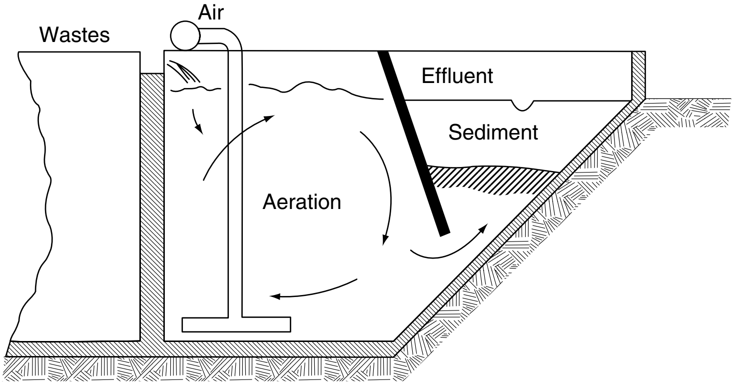

FIGURE 8.8. Complete-mixing activated-sludge system (adapted from McKinney et al. 1958).

TABLE 8.3
Summary of Disposal Systems

Company	*Type of waste*	*Injection rate, gpm*	*Injection pressure, psi*	*Subsurface depth of wells, feet*	*Formation age, type, and name*	*Total cost of system ($)*	*Date started*	*Problems*	*Solutions and remarks*
A	Brine; chlorinated hydrocarbons	200	500	12,045	Precambrian fractured gneiss (unnamed)	1,419,000	March 1962	Microorganisms in waste	
B	Clear 4% solution Na_2SO_4	300	45	295	Sandstone	—[a]	June 1951	None	
C	Masic waste, pH±10	70	1,000	6,160	Cambrian sandstone	250,000	Nov. 1960	Inadequate filtration	Larger filter planned
D	Magnesium; calcium hydroxides	200	Vacuum	400	Permian salt bed (Hutchinson)	—[a]	—[a]	None	
	Manufacturing waste, pH may change from 1 to 9 in hr	400	Vacuum	4,150					
E	Lachrymator waste from acrolein and glycerine units	700	150–170	1,960	Ordovician vugular limestone (Arbuckle)	500,000	Dec. 1957	Corrosion and water hammer	Heavier tubing planned
F	Aqueous solution—phenols, mercaptans, and sulfides	215	30–90	1,795	Pleistocene	135,000	1956	Sand incursion increased injection pressure	Backwashing every 4 months
					Pleistocene	30,000	Sept. 1959	Sand incursion	Periodic backwashing
					Pleistocene	—[a]	March 1960	Sand incursion	Periodic backwashing
G	Phenols; mercaptans; sulfides; brine	100	40–100	1,980	Devonian vugular limestone (Dundee)	—[a]	1950	None	

					Devonian vugular limestone (Dundee)	—[a]	None		
H	Phenols; chlorinated hydrocarbons	200	450	4,000	Silurian sandstone (Sylvania)	25,000	Aug. 1956	High wellhead pressure	Acidizing and fracturing
	Brine	200	150	4,000					
	Phenols; mercaptans; sulfides	50	—[a]	4,000					
I	Coke oven phenols; quench water	50	300	563	Devonian sandy limestone (Dundee); Traverse, Dundee and Monroe	400,000	1954	None	
J	Organic wastes	60	500	1,472	Permian sandstone	562,000	Jan. 1960	Microorganisms decreased injectivity	Formal-dehyde
K	Sulfuric acid waste	400	Vacuum	1,830	Ordovician vugular lime-stone (Arbuckle)	300,000	Feb. 1960	Mechanical failure of surface equipment	
L	Detergents; solvents; salts	254	280	1,807	Unconsolidated sand (Glorieta)	—[a]	April 1962	None	
M	38% HCl solution	14		1,110	Unconsolidated sand (Glorieta)	—[a]	1959	None	
N	Stripping steam condensate; cooling tower blowdown	50	10–20	1,110	Unconsolidated sand (Glorieta)	—[a]	1958	None	
	Aqueous petroleum refinery effluent	400	50–70	1,110					
O	Phenols; brine	75	400	7,650	Eocene sand and clay (Frio)	—[a]	1958	High injection pressure	Periodic acidizing

[a] Information not available.

continuous, the humus collected on the filter-bed surfaces is sloughed off continuously. Crushed stone, such as traprock, granite, and limestone, usually forms the surface material in the filter, although other materials such as plastic rings have proved very effective. The main advantages of plastic media include their light weight, chemical resistance, and high specific surface (i.e., square feet per cubic feet of bed volume). Because smaller stones provide more surface per unit of volume, the contact material must be small to support a large surface of active film, but not so small that its pores become filled by the growths or clogged by accumulated suspended matter or sloughed film. Crushed stone, 3–5 inches in diameter, is used, with the smallest stone at the top. The integral parts of a trickling-filter system are the distribution nozzles, contact surface, and underdrain units. This process may be summarized as follows:

1. An active surface film grows on the stone or contact surface.
2. Concentration of colloidal material and gelatinous matter occurs.
3. These adsorbed substances are attacked by bacteria and enzymes and reduced to simpler compounds, so that NH_3 is liberated and oxidized by chemical and bacterial means, giving a gradual reduction of NH_3 and an increase of NO_2 and NO_3 (Figure 8.9).
4. A flocculent, humus-like residue or sludge, containing many protozoa and fungi accumulates on the surface. When it gets too heavy, it will slough off and resettle (a continuous process with biofilters). Part of the oxygen is supplied by spraying waste, blowing air into the filter, or allowing waste to drip into the filter. Another portion is supplied by convection due to the temperature difference between the incoming waste and the bed. The larger the surface, the greater the number of bacterial organisms that come into contact with the liquid to be purified; the greater the number of organisms, the higher the purification of the liquid. The smaller the pieces of rock in the surface media, the greater the purification; too-small particles, however, promote clogging. To summarize, trickling filters act as both strainers and oxidizers.

Zobell (1937) first pointed out the importance of providing solid contact surfaces to further the physiological activities of bacteria growing in dilute nutrient solutions, as

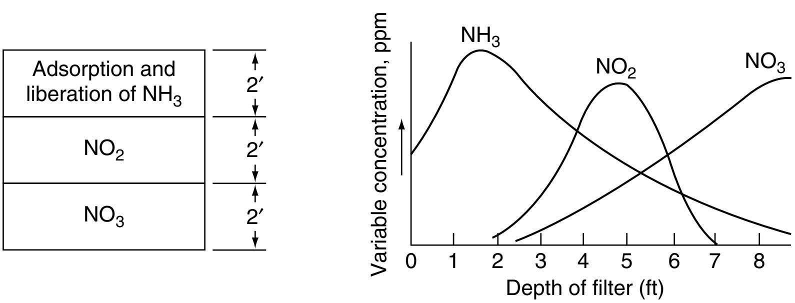

FIGURE 8.9. Changes in nitrogen occurring in filter.

most industrial wastes are. The following phenomena, according to Zobell, cause this increase in biological oxidation:

1. Solid surfaces make possible the concentration of nutrients and enzymes by adsorption to the surface.
2. The interstices between bacterial cells and surfaces act as concentration points; they retard the diffusion of exoenzymes and metabolites away from the cell, thereby favoring both digestion and adsorption of foodstuffs.
3. The interstices between surfaces and cells produce optimum conditions for oxidation-reduction and other physicochemical reactions.
4. Surfaces function as attachment points for microorganisms, which are obligatory periphytes.

A typical standard-rate, stone-bed trickling filter provides about 100 ft^2 of surface material per square foot of ground on which the filter is constructed. Velz (1948) proposed the performance equation for trickling filters as

$$L_d/L = 10^{-kd},$$

where L_d is the removable fraction of BOD remaining at depth D, L is total removal, k is the logarithmic extraction rate, and D is the depth of the bed. The reader will note the similarity between this equation and the monomolecular rate of decomposition of organic matter in streams:

$$L1/L = 10^{-kt}.$$

The student should realize that the contact time in a filter is relatively short, compared with an activated-sludge process. However, the organic matter (bacterial food) resides in the bed longer than computed from the detention time. Howland (1957) has contributed to our knowledge of contact time in filters. Assuming that a sheet of water is flowing steadily down an inclined plane under laminar flow conditions, he expresses the contact time as

$$T = (3v/gs)^{1/3}\ (1/q^{2/3}),$$

where T is the time of flow down the inclined plane, l is the length of the plane, s is the sine of the angle that the plane makes with the horizontal, g is the acceleration due to gravity, v is the kinematic viscosity of water (μ/p), and q is the rate of flow per unit width of the plane.

Howland (1957) indicates that the amount of oxidizable organic matter removed in a filter depends directly on the length of time of the flow. He recommends a deep filter containing the smallest practical media to achieve an optimum contact time and maximum efficiency. Although some researchers recommend shallower filters and larger stone to reduce both initial and operating costs, the tendency today appears to be to follow Howland's recommendations because engineers want an increasing degree of removal of BOD. Still, because of clogging and head-loss difficulties, there is a limit to how deep a bed and how small a stone size one can utilize.

Ingram (1956) suggests the following drawbacks of trickling filters: They occupy too much space; they exhibit seasonal variation in efficiency; clogging and pooling present problems; and there are limitations on the strength of sewage applied. He proposes a trickling-filtration process called "controlled filtration," which utilizes deep filters (18–24 ft). He was able to achieve greater than 70% BOD removal (the removal expected in high-rate filters loaded at a normal rate of 20 mgad and 1,300 lb of BOD/acre-ft/day) with a minimum hydraulic loading of twice and an organic loading of 1-1/2 to 10-1/2 times these normal standards. His experimental filter is shown in Figure 8.10.

Behn (1960) points out that deviations from the usual reaction rates sometimes occur because of the waste temperature and degree of filter saturation. Rankin (1953)

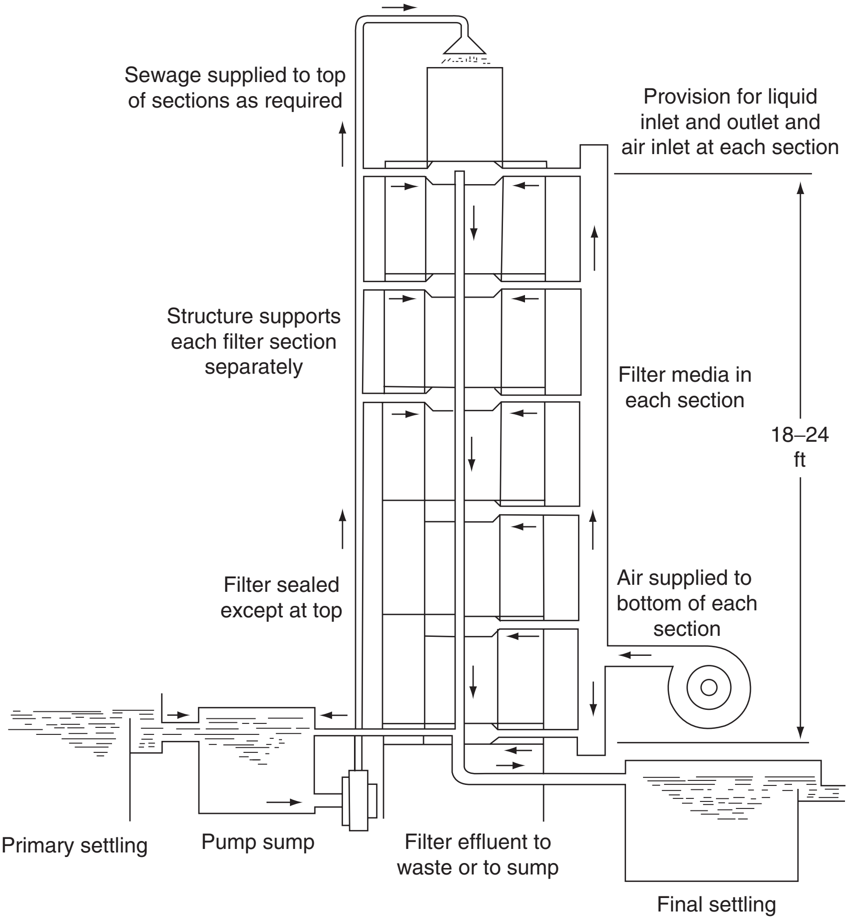

FIGURE 8.10. Diagram of experimental controlled-filtration system (adapted from Ingram 1956).

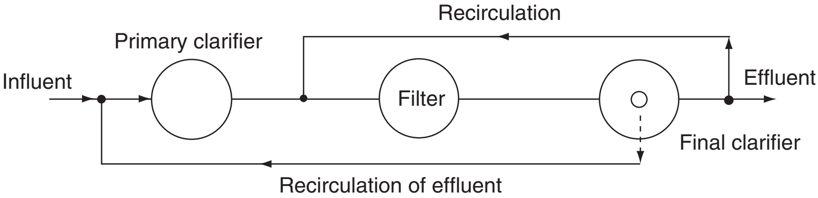

FIGURE 8.11. Single-stage trickling filter (with recirculation).

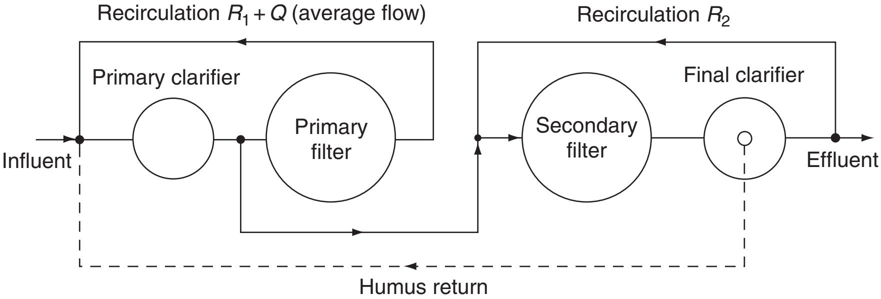

FIGURE 8.12. Two-stage series-parallel biofiltration process.

was concerned with recirculation of filter effluent and concludes, from a study of a number of treatment plants, that performance appears to depend primarily on the ratio of recirculation to raw wastewater flow, rather than on dosing rate, loading of the filter, or depth of filter (within the ranges studied). In smaller plants, with only one filter, single-stage filters appear to be most feasible, while for larger plants, where multiple filters are necessary or where stronger wastes are being treated, a two-stage series-parallel arrangement of filters yields a better effluent than single-stage filters with the same tank and filter capacity and the same volume of recirculated liquor. Diagrams of each of these systems are shown in Figures 8.11 and 8.12.

Spray Irrigation

Spray irrigation is an adaptation of the familiar method of watering agricultural crops by portable sprinkling-irrigation systems; wastes are pumped through portable pipes to self-actuated sprinkler heads. Light weight aluminum or galvanized piping, equipped with quick-assembly pipe joints, can be easily moved to areas to be irrigated and quickly assembled. Wastes are applied as a rain to the surface of the soil, with the objective of applying the maximum amount that can be absorbed without surface runoff or damage to the cover crops. A spray-irrigation system is composed of the following units: (1) the land on which to spray; (2) a vegetative cover crop to aid absorption and prevent erosion; (3) a mechanically operated screening unit; (4) a surge tank or pit;

(5) auxiliary stationary screens; (6) a pump that develops the required sprinkler-nozzle pressure; (7) a main line; (8) lateral lines; and (9) self-actuated revolving sprinklers operating under 35–100 psi nozzle pressure.

With good cover crops (dense low-growing grasses) and fairly level areas, waste to a depth of 3–4 inches can be applied at a rate of 0.4–0.6 in./hr. The process is generally limited to spring, summer, and autumn. In a study of citrus wastes, Anderson et al. (1966) found that aerobic conditions are maintained without odors to a depth of at least 3 ft.

Your author found this method of treatment quite effective for removing dissolved organic matter from vegetable cannery waste in western New York State.

Wet Combustion

"Wet combustion" is the process ("Wet Combustion of Wastes" 1955) of pumping organics-laden wastewater and air into a reactor vessel at elevated pressure (1,200 psi) (Figure 8.13). The organic fractions undergo rapid oxidation, even though they are dissolved or suspended in the waste. This rapid oxidation gives off heat to the water by direct convection, and the water flashes into a stream. Inorganic chemicals, which are present in many industrial wastes, can be recovered from the steam in a separate chamber. Heat from an external source is applied just to start the process; thereafter, it requires only 12–20% of its own heat to maintain itself. The remaining 80–88% can be utilized as process steam or to drive turbines for electrical or mechanical power. This process has a good potential where steam is essential and inexpensive enough to justify the cost of the equipment and where the inorganic chemicals in the waste are worth recovering and

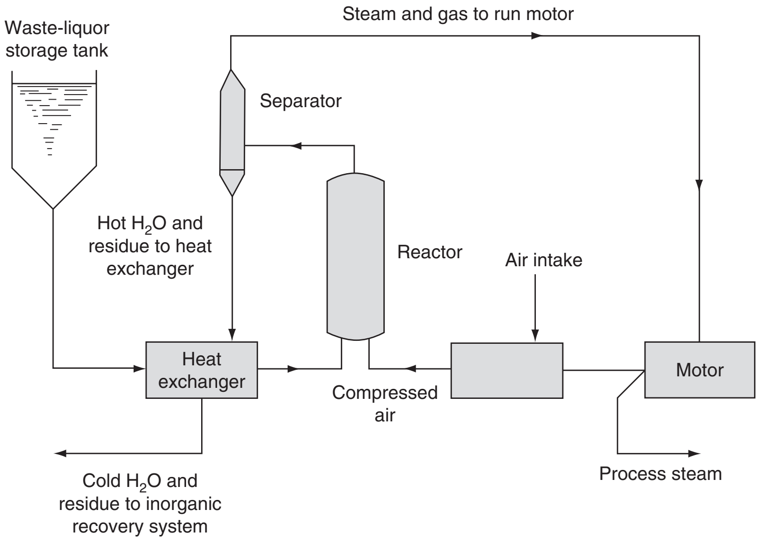

FIGURE 8.13. Schematic arrangment of wet-combustion–process units.

reusing. The wet combustion process can maintain itself only when the waste has a high percentage of organic material (usually about 5% solids and 70% organic).

Anaerobic Digestion

“Anaerobic digestion” is a process for oxidizing organic matter in closed vessels in the absence of air. The process has been highly successful in conditioning sewage sludge for final disposal. (Because digestion is primarily used for the treatment of sludge, rather than liquid wastes, the theory of its operation is described in more detail in Chapter 9.) It is also effective in reducing the BOD of soluble organic liquid wastes, such as yeast, cotton-kiering, slaughterhouse, dairy, and white-water (paper-mill) wastes. Generally, anaerobic processes are less effective than aerobic processes, mainly because of the small amount of energy that results when anaerobic bacteria oxidize organic matter. Anaerobic processes are, therefore, slow and require low daily loadings and/or long detention periods. However, because little or no power need be added, operating costs are very low. Where liquid waste volumes are small and contain no toxic matter and there are high percentages of readily oxidized dissolved organic matter, this process has definite advantages over aerobic systems. The pH in digesters must be controlled to near the neutral point.

Buswell and Hatfield (1939) proposed the following general equation for conversion of organic matter in industrial wastes to carbon dioxide and methane:

$$C_nH_aO_b + (n - a/4 - b/2)\ H_2O$$
$$= (n/2 - a/8 + b/4)\ CO_2 + (n/2 + a/8 - b/4)\ CH_4$$

In the United States, anaerobic treatment plants have been built to treat yeast, butanol-acetone, brewery, chewing gum, and meatpacking wastes. In a review of British practices, Pettet et al. (1959) found that slaughterhouse waste appeared to respond extremely well to anaerobic digestion, although up to 1959, there were no full-scale anaerobic-digestion plants in Great Britain. In the United States, BOD reductions of 60–92% have been attained with all these wastes, at loadings of 0.003–0.191 lb of BOD/ft^3 of digester per day. Concentrations of organic matter ranged from 1,565 to 17,000 ppm BOD.

Mechanical Aeration System

“Cavitation” is a typical process for mechanical aeration of wastes. The complete cavitator assembly consists of a vertical-draft tube with opening for connection to the influent pipe and a rotor assembly of the multiblade type, supported by an adjustable ball thrust bearing mounted at the motor level. The rotor is mounted on a stainless-steel shaft and the entire unit, including the draft tube, is supported by a structural steel bridge. A cross section is shown in Figure 8.14 (Schultze and Foth 1955). As soon as the rotor exceeds a certain critical speed, air is drawn in from the atmosphere through

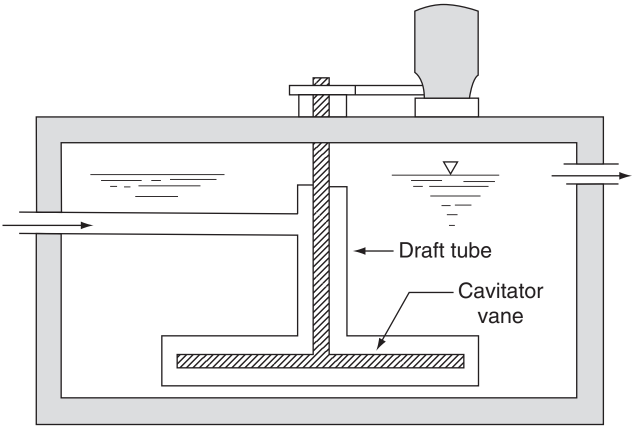

FIGURE 8.14. Typical cavitator system.

the vertical hollow tube and dispersed into the waste. The rotor creates a zone of cavitation in its turbulent trail and air moves in to fill the areas of rarefield under pressure. The amount of air that is being entrained depends on the size and shape of the rotor, the rotations per minute (rpm), and the water depth. The manufacturers claim that their system uses at least 25% of the available oxygen in the air, in contrast with conventional aeration equipment, which uses only 5%. At least one waste-treatment plant (dealing with canning wastes and sewage) attained more than 90% BOD removal with an air supply of 110 ft^3/lb of BOD per day. Operational costs (Schultze and Foth 1955) were $12.80 per day for an equivalent population of 12,000 persons. A modification to this system employs mechanical mixing by a rotor submerged (but near the surface of) the wastewater. Power costs are thus reduced, with no apparent loss of aeration or mixing efficiency. This system promises to be the most economical one for secondary treatment of wastes with a highly dissolved organic content.

Well Injection

Disposal of wastes containing dissolved organic matter by injecting them into deep wells has been successful in areas of low or nonexistent stream flow, especially when wastes are malodorous or toxic and contain little or no suspended matter. Deep-well injection has been used successfully to dispose organic solutions from chemical, pharmaceutical, petrochemical, paper, and refinery wastes; in addition, many inorganic solutions may be disposed of in this manner. To be effective, the wastes must be placed in a geological formation, which prevents the migration of the wastes to the surface or to groundwater supplies. The rock types most frequently used are the more porous ones such as limestones, sandstones, and dolomies because the porosity may help develop a filter cake that plugs the well. Other factors, in addition to geology, to be considered are depth and diameter of well, injection pressures, and the volume and characteristics of the wastes. At the end of 1966, there were 78 industrial disposal wells in the United States, most of which were used for chemical and refinery wastes (86%); most were less than 4,000 ft deep (74%), disposed of less than 400 gpm/well (87%), and operated at less than 300 psi (57%). Costs of injection disposal installations vary from $30,000 for a shallow (1,800-ft) well not requiring pretreatment to more than $1,400,000 for a very deep (12,000-ft) well with intricate pretreatment. Actual costs vary depending on depth, surface equipment, pretreatment, diameter of well, injection pressure, variability of composition of wastewater, and availability of drilling equipment.

Donaldson (1964) reported on a wide variety of industrial wastes being injected into formations ranging in age from Precambrian to modern day. In the United States up to 1964, more than 30 wells, ranging in depth from 300 to 12,000 ft, were being used for waste disposal into subsurface formations, which include unconsolidated sand, sandstone, regular limestone, and fractured gneiss. Although subsurface injection offers an economical method of final disposal where receiving water is inadequate to carry the wastewater away safely, circumstances can limit its effectiveness (e.g., the area lacks suitable underground formations for waste injection, the initial capital expense is excessive, or the pretreatment required may be too extensive and expensive).

The industrial-waste engineer must work closely with a geologist familiar with the subsurface formations in the area to select the proper waste-disposal zone. A well is drilled and core samples are analyzed for specific characteristics such as permeability and reactivity with the waste. Tests are performed to determine the injection pressure required at various wastewater flows.

Schematic drawings of typical complete subsurface waste-disposal systems are shown in Figures 8.15 and 8.16. Although cement tanks up to 50,000-gallon capacity are commonly employed within the basement of a factory, large, shallow open ponds may be used where land is available and where some settling and oxidation are required as pretreatment. The oil separator is required for petroleum refinery wastes, because oil tends to plug disposal formation and the oil can be recovered and reused. The usual

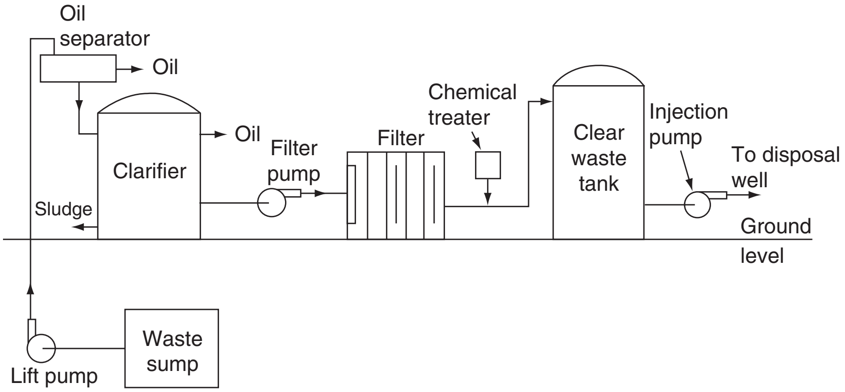

FIGURE 8.15. Typical surface equipment for deep-well waste injection from waste sump underground (from Bureau of Mines Information Circular no. 8212).

separator consists of a tank with many internal baffles to cause the oil to separate and rise. If a clarifier is then used, heavier material such as dirt, resin flocs, and suspended grease can settle out. Mechanical equipment such as sludge rakes and surface skimmers can also be used with this equipment. Because not all solids are completely removed by the treatment thus far described, filters are then used to protect sand or sandstone formations from plugging. The screens are usually metal and coated with diatomaceous earth, but in some situations, sand filters are preferred. If wastes contain slime that will form bacteria or fungi, a suitable bactericide (such as quaternary amines, formaldehyde, chlorinated hydrocarbons, chlorine, or copper sulfate) is used to control their detrimental effects. The clear-water storage tank is normally equipped with a float switch designed to operate the injection pump at certain liquid levels. The size and type of injection pump are controlled by wellhead pressure, wastewater flow, and wastewater characteristics such as pH and corrosiveness. The multiplex piston pump is most commonly used when wellhead pressures of more than 150 psi are required, whereas single-stage centrifugal pumps are used at lower pressures.

To construct the well, first a 15-in.-diameter hole is drilled to 200 ft below the deepest freshwater aquifer and a 10 1/2-in. (O.D.) casing is set and cemented to the surface. Next, a 9-in.-diameter hole is drilled to the bottom of the potential disposal formation, a 7-in. (O.D.) casing is set at the total depth of the hole, and cement is circulated in the annulus between the injection casing and the 9-in. hole to the surface (Figure 8.16). This method has been proven to seal off water aquifers from the well and

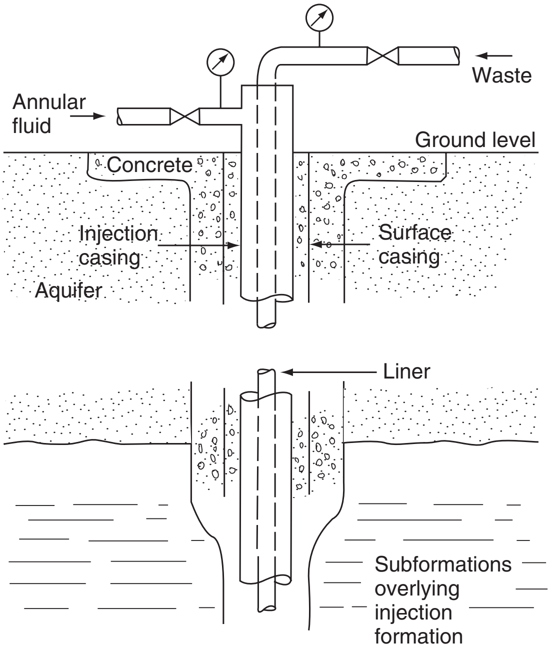

FIGURE 8.16. Typical injection well (from Bureau of Mines Information Circular no. 8212).

to protect other water resources. Table 8.4 summarizes Donaldson's (1964) findings for 20 separate installations, presenting much valuable information such as costs, associated problems, well depth, injection pressures, and formation type.

For the disposal of acid wastes, there are five requirements for deep-well disposal: (1) a satisfactory disposal horizon; (2) a horizon filled with saltwater; (3) a horizon located at a sufficient depth; (4) a suitable cap rock; (5) a waste compatible with the natural water in the disposal horizon. The possible dangers of deep-well disposal include (1) contamination of portable water supplies either by lateral migration to existing unplugged dry holes or producing wells, or by vertical migration through the subsurface, or by vertical migration due to mechanical failure; and (2) possible movements along old fault planes. The representative cost for a 4,000-ft well is \$450,000, which includes

TABLE 8.4
Summary of Disposal Systems

Company	*Type of Waste*	*Injection Rate, gpm*	*Injection Pressure, psi*	*Subsurface Depth of Wells, ft*
A	Brine; chlorinated hydrocarbons	200	500	12, 045
B	Clear 4% solution Na_2SO_4	300	45	295
C	Masic waste, pH±10	70	1,000	6,160
D	Magnesium; calcium hydroxides	200	Vacuum	400
	Manufacturing waste, pH may change from 1 to 9 in hr	400	Vacuum	4,150
E	Lachrymator waste from acrolein and glycerine units	700	150–170	1,960
F	Aqueous solution—phenols, mercaptans, and sulfides	215	30–90	1,795
G	Phenols; mercaptans; sulfides; brine	100	40–100	1,980
H	Phenols; chlorinated hydrocarbons	200	450	4,000
	Brine	200	150	4,000
	Phenols; mercaptans; sulfides	50	—[a]	4,000
I	Coke oven phenols; quench water	50	300	563
J	Organic wastes	60	500	1,472
K	Sulfuric acid waste	400	Vacuum	1,830
L	Detergents; solvents; salts	254	280	1,807
M	38% HCl solution	14		1,110
N	Stripping steam condensate; cooling tower blowdown	50	10–20	1,110
	Aqueous petroleum refinery effluent	400	50–70	1,110
O	Phenols; brine	75	400	7,650

[a] Information not available.

the cost of well and equipment, aboveground pumping and equipment, and holding-tank and collection equipment.

The reader may use the following checklist in the design of deep-well disposal systems:

A. State laws and legal aspects
    1. State recognition of this method
    2. Subsurface trespass
B. Geology
    1. Employment of geologist or well contractor
    2. Disposal formation
        a. Porosity
        b. Permeability
        c. Composition (sandstone or limestone)
C. Waste characteristics
    1. Volume reduction
    2. Injection flow rate
    3. Injection pressure
    4. Corrosiveness
    5. Biological effects
D. Surface equipment needs
E. Wells
    1. Number
    2. Size
    3. Monitoring
F. Economics

Following years of reporting on the use and misuse of deep-well injection of wastes, I have arrived at a conclusion that although this method of treatment may provide temporary respite from environmental concerns, it will eventually cause damage of some kind, somewhere, and to varying extents. It is truly only a temporary solution.

Foam Phase Separation

Figure 8.17 illustrates the equipment used for foam phase separation. A sparger producing small gas bubbles (usually air) causes these bubbles to rise through the liquid and adsorb surface-active solutes and suspended matter. When the bubbles reach the surface, a foam forms, which is forced out of the foamer, collapsed, and discharged as a concentrated waste.

Assume the following: (1) complete mixing in the foamer; (2) sufficient depth of liquid to reach maximum solute adsorption of the gas–liquid interface; (3) constant liquid density; (4) no bubble rupture in the foam phase; and (5) negligible volume of the liquid layer containing the surface excess of solute. At this point, the material-balance equation,

$$CF - CB = 1{,}000\ G/F\ rB\ S,$$

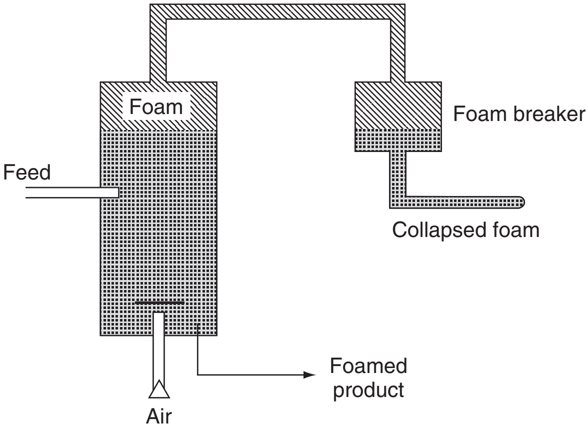

FIGURE 8.17. A column foam fractionator.

where CF and CB are feed and bottom product concentrations in mg/liter, G is the volumetric gas rate in liters/minute, rB is solute surface excess corresponding to CB in mg/cm^2, and S is the specific surface of bubbles in foam phase in cm^2/cc.

At flows of air to liquid feed of G/F = 3, it is reported that the COD is reduced by 25% and alkylbenzene sulfonate (ABS) concentrations are reduced by 50–75%. At air rates of 1.5 liters/mg of ABS in secondary effluents, removals of 0.4 ppm ABS have been reported. The success of the process, in general, depends on the foamability of the liquid waste, which is said to be of low order of magnitude. Bruner and Stephen (1965) have calculated foam separation costs (not including the foamate disposal) as follows:

mgd	cents/1,000 gal.
1	3.6
10	1.9
100	1.4

Shoen et al. (1962) used this treatment successfully to separate radium from uranium-mill wastewater. They found the pH of the wastewater very important in selecting foaming agents. An increase in foaming agent will generally produce a similar increase in foam during treatment. Grieves and Crandall (1966) also experimented with both iron and alum as coagulants using bentonite as an aid in foaming low-quality waters.

Brush Aeration

According to Pasveer (1959), the brush aeration system was evolved between 1925 and 1930 by Kessener for use in the activated-sludge process. It is essentially an extended aeration process providing more than 24 hours of aeration. Since the 1930s, it has found

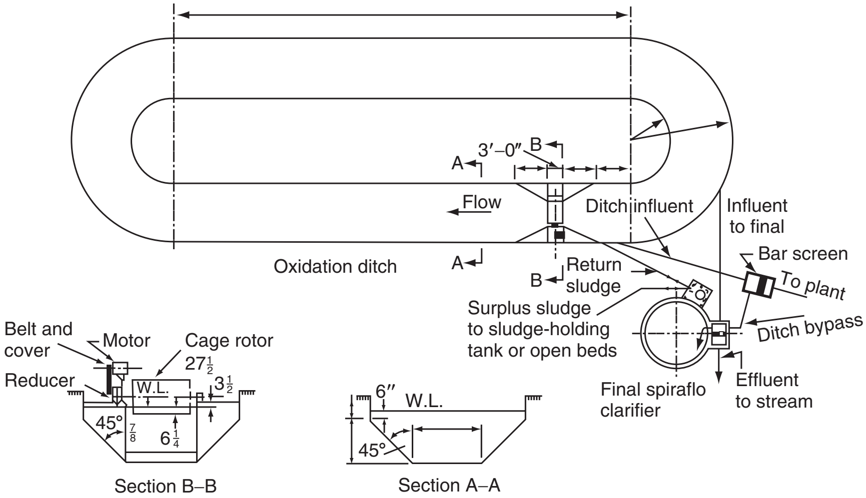

FIGURE 8.18. Typical layout of an oxidation ditch treatment plant (courtesy Lakeside Engineering Corp.).

application, particularly in the Netherlands and in a few plants in Britain, and about a dozen plants were constructed in Canada and the United States before 1964 (Ontario Water Resources Commission 1964) (Figure 8.18). Most of these aeration systems are installed in "oxidation ditches." The design of the oxidation ditch combines an aeration tank and a holding tank in a single unit; the aeration rotor circulates the mixed waste through the whole ditch by means of the rotating cage, but aeration occurs only in the vicinity of the rotor. The rotor is fixed at both ends and set transversely across the aeration ditch and rotates in the direction of waste flow. Aeration is obtained by means of long, rectangular, angle irons welded to the rotating cage. Although the results have been obtained mostly with domestic sewage, it is apparently adaptable to any organic industrial waste.

Subsurface Disposal

Three other methods of disposing dissolved organic wastes below the ground surface are injection, placement in underground cavities, and spreading. Because injection is discussed in some detail in the section "Well Injection" earlier in this chapter, and placement in underground cavities is limited to either small volumes of wastes or particular situations of subsurface formation, they will only be mentioned here as possibilities. Koenig (1964) reported, however, that in 1956, 244 cavities were used for storage, mostly for hydrocarbons and mostly in salt mines.

"Spreading" may be defined as the dispersal of liquid wastes on the ground in order to enhance their infiltration into it. Reclamation of wastewaters by spreading on land, with subsequent withdrawal of groundwater, has been extensively practiced, mostly for secondary sewage effluents. Infiltration rates govern the use of this method, while

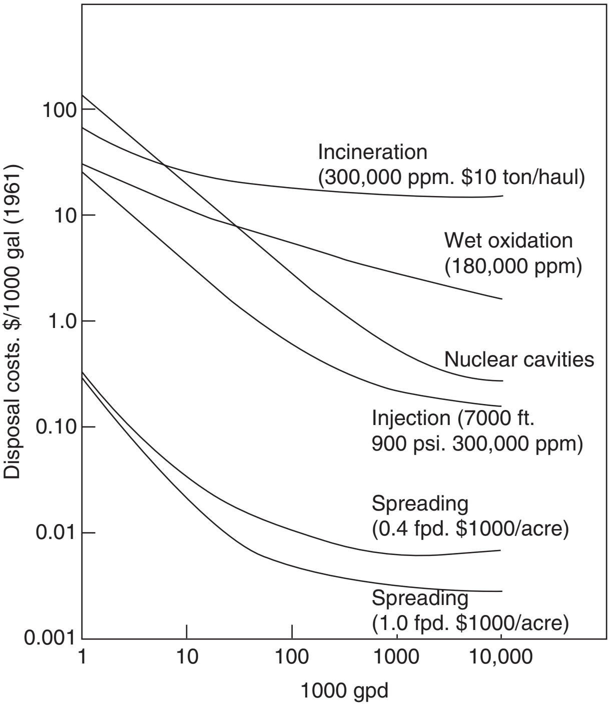

FIGURE 8.19. A comparison of unit disposal costs (1961 figures) (adapted from Koenig 1964).

ultimate effects on underground water supplies govern its acceptability. Because of numerous physical limitations, this method should be considered mainly for small volumes of concentrated organic wastes in particularly suited soils. Koenig (1964) gave comparative costs for this method of disposal and for injection, wet oxidation, and incineration (Figure 8.19).

The Bio-Disc System

The Bio-Disc system was developed independently in West Germany (by Harmann and Pöpel) and the United States (by Welch and Antonie).[1] It consists of a series of flat parallel discs that are rotated while partially immersed in the waste being treated. Biological slime covers the surface of the discs and adsorbs and absorbs colloidal and dissolved organic matter present in the wastewater. Excess slime generated by synthesis of the waste materials is sloughed off gradually into the mixed

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[1] For references, see the section on Bio-Disc in the "Suggested Reading" section at the end of this chapter.

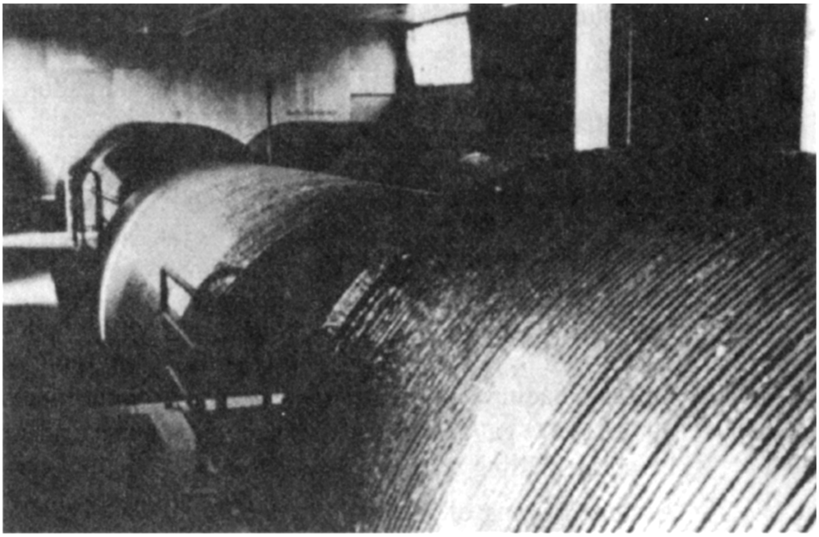

FIGURE 8.20. Rotating biological contractor (RBC) disc system (courtesy Allis Chalmers Company).

liquor and subsequently separated by settling (Figure 8.20). The rotating discs carry a film of the wastewater into the air where it absorbs the oxygen necessary for aerobic biological activity of the slime. Disc rotation also provides contact between the slime and the wastewater. Thus, the rotating discs provide (1) mechanical support for a captive microbial population; (2) a mechanism of aeration, the rate of which can be adjusted by changing the rotational speed; and (3) contact between the biological slime and the wastewater, the intensity of which can be varied by changing the rotational speed.

Use of closely spaced parallel discs achieves a high concentration of active biological surface area. This high concentration of active organisms and the ability to achieve the required aeration rate by adjusting the rotational speed of the discs enables this process to give effective treatment to highly concentrated wastes. At a loading of 11 lb of BOD/day/1,000 ft^2 of surface area, 90% BOD removal is obtained in 2,000 ppm BOD dairy waste. Secondary treatment of domestic sewage is accomplished with a retention time of 1 hour or less, and 90% BOD reduction is obtained at a loading of 5 lb BOD/day/1,000 ft^2. Because a buoyant plastic material is used for the discs and negligible head loss is encountered through the rotating biological contactor (RBC) itself, the power requirement for this process is very low. Its simplicity of construction and operation has demonstrated that minimal unskilled maintenance is all that is required for efficient operation.

The RBC process has gained wide acceptance in Europe. During a 10-year period, more than 400 Bio-Disc plants were constructed there, ranging in size from 24,000 to 55,000 population equivalents for treatment of domestic and industrial wastes. This process is now being introduced commercially to the United States.

Biological Treatment Design

Example

An integrated pulp and paper mill generates wastewater from its various operations with the following characteristics:

	Process A	*Process B*
Flow	3.5 mgd	6.0 mgd
BOD	2,500 mg/liter	1,100 mg/liter
TSS	1,000"	450 mg/liter
pH	10	6.9
Temperature: summer	25°C	25°C
winter	15°C	15°C

The proposed treatment scheme consists of flow equalization, primary clarification, activated sludge, secondary clarification, and final treatment in aerated stabilization basins. Design the treatment units given the following design criteria:

Activated-sludge effluent:
BOD = 100 mg/liter
TSS = 100 mg/liter
pH = 6.5–9.0
K = 0.0015 liters/mgd at 20°C
Y = 0.6
b = 0.01/day
O = 1.05
MLSS = 3,000 mg/liter
MLVSS = 2,500 mg/liter
F/M = 0.15–0.4
Minimum solids retention time = 10 days
Sludge recycle rate = 40%

Solutions

Equalization

Combined flow Q = 9.5 mgd

Combined BOD = (3.5 × 2,500 + 6.0 × 1,100) / (9.5)
= 1,616 mg/liter

Combined TSS = (2.5 × 1,000 + 6.0 × 450) / (9.5)
= 547 mg/liter

Detention time = 15 minutes

Volume of equalization tank = $Q_t = (9.5 \times 15 \times 10^6) / (60 \times 24)$
$= 99{,}000$ gallons
Mixing requirements: @ 0.05 hp/10^3 gal
$= 0.05 \times 99 = 4.95$ hp
Aeration requirements: @ 1.5 ft^3 air/10^3 gal_3
$= 1.5 \times 99 = 148.5$ ft^3

Primary Clarifications
Surface loading or overflow rate (OFR) ranges generally from 500 to 1,000 gal/day/ft^2. Select the loading based on settling tests:

Assume loading of 750 gal/day/ft^2

Surface loading (u) = Q/A
Area A = Q/u = $(9.5 \times 10^6) / 7{,}540 = 12{,}667$ ft^2
Diameter of clarifier = $12{,}667 \times 4$
= 127 ft

Detention time ranges from 2 to 4 hours.
Assume detention time of 3 hours.

Volume of clarifier = Q_t
(V) = $9.5 \times 10^6 \times (3 \text{ hr}) / (24 \text{ hr/day})$
= 1,187,500 gal
@ 7.48 gal/ft^3
V = (1,187,500) / (7.48) = 158,757 ft^3

Depth of clarifier = V/A
= (158,757) / (12,667)
= 12.5 ft

Depth generally ranges from 10 to 15 ft, so calculated depth is within range.

Circumference of clarifier = D

= × 127 = 399 ft.

Check effluent weir loading (ranges from 10,000 to 25,000 gpd/ft)

Weir loading = $(9.5 \times 10^6) / (399) = 23{,}810$ gpd/ft is within range

Activated Sludge
Assume 50% BOD removal in primary clarifier. Therefore, BOD in influent to activated-sludge unit is 808 mg/liter.

Calculate reaction range (k) for summer and winter temperatures:

$$K_T = K_{20}\,Ø^{T-20}\quad Ø = 1.04$$

$$\text{Summer: } k_{25} = (0.0015)1.04^{25-20} = 0.00183 \text{ liters/mg-day}$$
$$\text{Winter: } k_{15} = (0.0015)1.04^{15-20} = 0.00123 \text{ liters/mg-day}$$

Next, calculate volume of aeration tank for summer and winter conditions.

Summer Condition

$$F/M = k_{Sc}$$
$$= 0.00183(100) = 0.183 \text{ days}^{-1}$$

1/SRT = Y (F) / M – b (Use this value since greater than minimum design criteria.)

$$= 0.64(0.183)^{-1} - 0.01$$
$$= 0.017 \text{ days}$$

Therefore, SRT = 9.4 days.
Use SRT = 10-day minimum per design criteria.

$$XV = [Y(S_o - S_c) \text{ SRT Q}] / [1 + b\,(\text{SRT})]$$
$$= [0.64(808–100)\ 10(9.5) / [1 + 0.01(10)]$$
$$= 39{,}133$$
$$@ \text{ MLVSS} = X = 2{,}500 \text{ mg/liter}$$

Therefore, volume of aeration tank = (39,133/2,500) = 15.6 million gallons.

Winter Conditions

$$F/M = k_{Sc}$$
$$= 0.00123(100) = 0.123 \text{ days}^{-1}$$

Use F/M = 0.15 per minimum design criteria.

$$1/\text{SRT} = Y\,(F)/M - b$$
$$= 0.64(0.15) - 0.01$$
$$= 0.086 \text{ days}^{-1}$$

Therefore, SRT = 11.6 days. (Use this value for SRT, since greater than minimum design criteria.)

$$\begin{aligned} XV &= [Y(So - Sc)\ SRT] / [1 + b\ (SRT)]\ Q \\ &= [0.64(808 - 100)\ 11.6(9.5) / [1 + 0.01(11.6)] \\ &= 44{,}584 \end{aligned}$$

Therefore, volume of aeration tank = 44,584/2,500
= 17.8 million gallons

Thus, the larger volume required for winter conditions determines the design volume of the aeration tank.

$$\text{Detention time} = V/Q = 17.8/9.5 = 1.87 \text{ days}$$

Check F/M ratio.

$$\begin{aligned} F/M &= (9.5 \text{ mgd} \times 808 \text{ mg/liter} \times 8.34) / (17.8 \text{ mg} \times 2{,}500 \text{ mg/liter} \times 8.34) \\ &= 0.17 \text{ days}^{-1} \end{aligned}$$

Check at maximum flow condition.

$$\begin{aligned} F/M &= (9.5 \times 808 \times 8.34) / (13.3 \times 2{,}500 \times 8.34) \\ &= 0.23 \end{aligned}$$

Both F/M are within design criteria range.

Waste Sludge Production

$$SRT = \text{lbs MLSS/lbs solids wasted/day} + \text{lbs solids in effluent}$$

Calculate waste sludge production for minimum SRT = 10 days.

$$\begin{aligned} SRT &= [17.8 \text{ mgal} \times 8.34 \times 3{,}000 \text{ mg/liter}] / [Sw + (9.5 \text{ mgd} \times 8.34 \times 100 \text{ mg/liter}] \\ 10 &= 445{,}356/Sw + 7{,}923 \end{aligned}$$

Therefore, sludge wasted S_w = 36,613 lbs/day.

Calculate oxygen requirements:

$$\begin{aligned} \text{lbs oxygen requires/day} &= y' \text{ (lbs BOD removed/day)} + b' \text{ (lbs MLVSS)} \\ \text{lbs BOD removed/day} &= 9.5 \text{ mgd} \times (808 - 100) \times 8.34 \\ &= 56{,}095 \text{ lbs/day} \\ \text{lbs MLVSS} &= 2{,}500 \text{ mg/liter} \times 17.8 \times 8.34 \times 371{,}130 \text{ lbs/day} \\ \text{lbs oxygen} &= 0.6(56{,}095) + 0.1(371{,}130) \end{aligned}$$

$$= 70{,}770 \text{ lbs/day}$$

$$= 2{,}950 \text{ lbs/hr}$$

Aeration horsepower requirements:

Oxygen transfer rate for design conditions is calculated as follows:

$$N = No\ [(B \times cS \text{ at } -cL) / (cSc)]\ 1.024\ T-20$$

Calculate transfer rate based on summer conditions.

$$N = 3.0\ [0.9 \times (8.5 - 2.0) / (9.2)]1.024^{25-20}\ (0.8)$$

$$= 1.7 \text{ lbs oxygen/hp-hr}$$

$$\text{horsepower} = 2{,}950 \text{ lbs/hp-hr}$$

$$= 1{,}735 \text{ hp}$$

Check power requirements to ensure adequate mixing in aeration tank. Assume approximately 100 hp/million gallons required for mixing.

$$1{,}735 \text{ hp}/17.8 \text{ mg} = 97.5 \text{ hp/million gallons}$$

Therefore, horsepower provided for aeration would be adequate for mixing in the aeration tank.

Final Clarifier

Solids loading to final clarifier is calculated as follows:

$$\text{Sludge recirculation} = 40\%$$

$$\text{Recirculation flow (R)} = 0.4 \times 9.5 = 3.8 \text{ mgd}$$

$$\text{Solids loading to clarifier} = (Q + R)\ \text{MLSS} \times 8.34$$

$$= (9.5 + 3.8)3{,}000 \times 8.34$$

$$= 332{,}766 \text{ lbs/day}$$

Final clarifier area is calculated based on requirement for thickening area and clarification area.

Thickening area is calculated assuming solids loading rate of 15 lbs/day/ft^2 (range 10–20 lbs/day/ft^2).

$$\text{Thickening area} = 332{,}766/15$$

$$= 22{,}184 \text{ ft}^2$$

Clarification area is calculated assuming an OFR of 600 gpd/ft^2 (range 400–1,000 gpd/ft^2).

$$\begin{aligned}\text{Clarification area} &= \text{Q/OFR}\\ &= 9.5 \times 10^6/600\\ &= 15{,}833\ \text{ft}^2\end{aligned}$$

Therefore, the thickening area governs.

$$\text{Area} = 22{,}184\ \text{ft}^2$$

Diameter of final clarifier = 168 ft.
Assume a detention time of 3 hours.

$$\begin{aligned}\text{Volume of clarifier} &= \text{Q}_\text{t}\\ &= 9.5 \times 10^6 \times 3\\ &= 1{,}187,\ 500\ \text{gal}\\ &= 1{,}187,\ 500/7.48\ \text{ft}^3\\ &= 158,\ 757\ \text{ft}^3\\ \therefore \text{Depth of clarifier} &= 158,\ 757/22{,}184\\ &= 7\ \text{ft}\\ \text{Depth of clarifier} &= 158{,}757/22{,}184\\ &= 7\ \text{ft}\\ \text{O.K. (range 5–15 ft)}&\\ \text{Check effluent weir loading} &= \text{Q/d}\\ &= 9.5 \times 10^6/168\\ &= 18,\ 008\ \text{gpd/ft}\\ \text{O.K. (range 10,000–20,000 gpd/ft)}&\end{aligned}$$

Collection and Reclamation (Scavenging)

The scavenger hauls, treats, reclaims, and disposes of a variety of industrial wastes acquired through contract of purchase from firms that do not choose to treat their own wastes.

Scavenging firms may be as varied as the customers they serve. Some small firms may only provide hauling and land-disposal services; others specialize in a single line of waste, such as solvents, which may be profitably reclaimed. Large firms may provide a full range of treatment and consulting services.

Recycling Laboratories (Canastota, New York), for example, specializes in the reclamation of solvents, particularly chlorinated hydrocarbons such as trichloroethylene. Typically, it purchases used solvents, redistills them, and then resells them at a profit. The company also handles some alcohols and thinners and, for a fee, will accept petroleum products, which it uses in its steam plant. Recycling Laboratories is a small and fairly new firm and most of its business comes from the immediate central New York area. It envisions expanding one line at a time as it acquires experience in dealing with different sorts of wastes.

Chem-Trol Pollution Services, Incorporated, of Model City, New York (near Buffalo), represents the other end of the spectrum. It is a large firm that operates on a 240-acre site with seven separate lagoons. Lagoon storage totals 6 million gallons, while closed-tank storage totals an additional 2 million gallons. It processes wastes using the following techniques: (1) filtration; (2) thermal oxidation (incineration); (3) neutralization; (4) distillation; (5) chemical fixation; and (6) physical separation (such as centrifuging). Residues are land filled. Many of its operating practices are subject to proprietary considerations but may be considered to generally follow the usual treatment techniques.

Advantages of scavenging treatment:

1. Economy of scale exists in larger plants.
2. Operating efficiencies other than scale—specialization, neutralization, and equalization—increase as the size of the operation increases.
3. Treatment expense is involved only for the small industrial plant, rather than capital investment.
4. Resource-recovery potential exists in the larger reclamation plant.

Disadvantages of scavenging treatment:

1. Newness of the field: There is neither a trade association nor a real trade publication. Relatively little information exchange occurs, particularly with regard to proprietary practices. Regulation and standards vary with locality.
2. Transportation expense, typically by truck, may be high.
3. Batch processes are usually necessary with attendant high labor and overhead costs.
4. Dependence on secondary markets is risky for the scavenger.
5. Poor public image may exist unless a proper public relations program is used.

Nevertheless, the scavenger fills a very real need in this time of increasingly strict environmental controls and is especially useful for the treatment of low volumes of highly concentrated organic wastes. The reader is directed to Nemerow (1995, Chapter 4) for a detailed description of reuse of wastes by scavenging.

Chemical Oxidation of Organic Matter

It has been long known and sometimes implemented in waste treatment that organic matter can be completely destroyed by chemical oxidation. Oxidants such as chlorine, hydrochloric acid, chlorine dioxide, permanganate, hydrogen peroxide, pure oxygen, ozone, hydroxyl radicals, and bromine and fluorine are all effective, in varying degrees, for this purpose. Generally, chemical oxidation was considered too costly or impractical for industrial-waste treatment. Expensive and often difficult-to-handle oxidizing chemicals were consumed in the process, and further, such complete destruction of organic wastes was not usually required. The cost effectiveness of chemical oxidation was usually questioned by waste-treatment engineers.

However, today's industry faces much more stringent discharge requirements. Contamination of our groundwater has made remediation a first-order objective. And because so many groundwater supplies serve as sources of drinking water, higher degrees of purification have become a necessity. This has led to renewed consideration of chemical oxidation as a viable and cost-effective treatment alternative.

Improved analytical instrumentation, coupled with a much wider spectrum of chemical identification, allows us to identify and measure contaminants in water in lower concentrations with greater precision. This has led to broader and more stringent water-quality standards—a driving force calling for the increased use of chemical oxidants for the removal of broad-spectrum organics. Chemical oxidation is effective especially in situations in which the waste concentration of the organic matter is high and a high degree of treatment is required, making treatment cost secondary to receiving-water quality. The process of chemical oxidation, when carried to its ultimate goal, yields carbon dioxide and water and usually releases heat because the reactions are exothermic. One example of this type of application by a chemical oxidant is that of hydrogen peroxide in combination with ferrous sulfate (at a pH of 3.5–4.0). According to Bigda [20A], when H_2O_2 splits into OH− and OH+, the ultra-active OH+ is more powerful than ozone, chlorine, or pure oxygen and combines with carbon found in organic compounds, breaking the double bonds and aromatic rings and removing hydrogen molecules. The combination of about 1 part of iron to 10 parts of peroxide is referred to as *Fenton's reagent*. It has been used in the treatment of wastes containing phenol, formic acid, and other organics from paint stripper rinse waters (Tyre et al. 1991; Watts 1992). Costs for treating 1,000 gallons of waste containing 1,000 ppm of phenol was reported to be about $0.14/gal (Tyre et al. 1991), including labor and power. Other researchers and engineers recommend using ozone (Murdock 1951) and chlorine (Chamberlain and Griffin 1952) as most effective in treating phenolic-type organics.

Miscellaneous

Ozonization

Organic matter in industrial wastewaters can be completely oxidized through contact and reaction with ozone (O_3). Ozone is a gas that is produced by passing oxygen through an electrical field. Approximately 11 kwh of electrical power is required to produce 1 lb of ozone from air. From 1.5 to 2.5 lb of ozone is used for each pound of dissolved organic matter oxidized. If pure oxygen is used instead of air as a source of ozone, the power requirements are reduced by about 50%. Small-size ozone-generating units, producing up to 75 lb of ozone per day, are available commercially for use by industries with small volumes of organic wastes. The ozone produced is usually dissolved in wastewater by injection nozzles or cavitation. This form of treatment has been found especially suited for oxidizing phenolic wastes. Ozone contact time can usually be kept to less than 30 minutes, especially for final or tertiary-type treatment, where organic matter concentration is relatively low and allowable effluent limits are also low.

Photolysis

The interaction of photocatalysts with radiation below about 4,200°A produces active oxygen species that destroy organic matter by complete oxidation to CO_2 and H_2O. Certain oxides, notably zinc oxide and titanium dioxide, are known to be photosensitizers or photocatalysts. Kinney and Ivanuski (1969) reported that photocatalytic oxidation of dissolved organic matter by irradiation of slurries of zinc titanate (Zn_2TiO_2), zinc oxide (ZnO), titanium dioxide (TiO_2), and beach sand by sunlamps was effective. Dissolved organic matter in a sample of domestic sewage was reduced 50% in 24 hours and 75% in 70 hours. The reaction appears to follow first-order kinetics in most cases. Zinc oxide appears to be superior for this purpose. At concentrations of 100–200 mg/liter of organic carbon, 80% of phenol, 67% of benzoic acid, 44% of acetic acid, 40% of sodium stearate, and 16% of sucrose were oxidized in 24 hours with 10 g/liter zinc oxide catalyst. Continued illumination reduced organic carbon to a few milligrams per liter in most cases. The photocatalytic properties of illuminated beach sand, which oxidized 87% of phenol in 72 hours, strongly suggest that photocatalysts are widely distributed in nature. Further, it suggests that photocatalytic oxidation is a mechanism whereby dissolved organic matter is oxidized in the natural environment of streams and lakes. The researchers (Kinny and Ivanuski 1969) suggested that three conditions must be satisfied to achieve oxidation of an organic molecule: (1) the molecule must be adsorbed at, or be in the vicinity of, the active site on the catalyst; (2) light energy of suitable wavelength (below about 4,200°A) must impinge on the active site; (3) dissolved oxygen must be present to replace the active oxygen species displaced by the radiation. From these considerations and with everything else being equal, the higher the concentration of contaminant, the faster the rate of oxidation. Thus, it would appear that photocatalytic oxidation will find its greatest utility in problems of industrial-waste treatment where massive contamination is involved. The researchers also believed that vigorous agitation at elevated temperature would favor faster kinetics, despite lower dissolved-oxygen levels.

Pure Oxygen Treatment

The Union Carbide Corporation has refined and improved upon a biological aeration system using pure oxygen in place of air. In this system, the aeration tanks are completely covered to provide a gas-tight enclosure above the mixed liquor. Both the liquid and the gas phase are staged with a concurrent flow of the gas and liquid through the multistage system. The feed wastewater, along with the recycled sludge, is introduced into the first stage together with the oxygen feed gas. The oxygen gas is fed into the enclosure above the mixed liquor. Mechanical agitation provides the required bulk fluid motion to maintain the sludge in suspension and to ensure a uniform liquid composition. Blowers in each stage recirculate the gas in the enclosure through the mixed liquor. The gas is piped through a hollow agitator shaft and dispersed into the mixed liquor through a rotating-sparger device. The pressure of the gas enclosures above the mixed liquor is automatically controlled at a few inches of water above atmospheric pressure. The oxygen gas is fed in direct proportion to the demand of the mixed liquor. The aeration gas flows freely from stage to stage with only a slight pressure differential to prevent back-mixing of the gas between adjacent stages. The mixed liquor exiting the final stage is passed into a conventional settler for clarification. The vent gas will usually comprise only about 10% of the volumetric flow rate of the oxygen feed gas and will be about 50% oxygen. Thus, it is claimed to be 95% efficient in oxygen transfer. The manufacturer claims high treatment-rate-performance capability of the oxygenation system. It reports more than 90% reductions in both BOD and suspended solids after shorter detention times and higher loadings than the conventional aeration activated-sludge treatment systems.

Example of Twentieth-Century Practice of Organic Dissolved Solid Removal

Banerjee (1997) used a laboratory four-step cross-flow RBC to remove organic phenol. He observed that removal of phenol improved at higher input phenol concentration. Temperature increase in the range of 13–36°C improved the removal. The major group of microbes in the RBC was *Pseudomonas*. He reported that phenolic wastewater up to a concentration of 420 g/m^3 could be treated effectively by this process.

Review Questions

1. Why has removal of organic dissolved solids long been the most important and most difficult phase of industrial-waste treatment?
2. What is the basis for most treatment processes for dissolved organic removal?
3. What is necessary for optimal biological treatment?
4. What are the advantages and disadvantages of lagooning? Of activated sludge?
5. Name and describe some modifications of the activated-sludge process.
6. What is the principle of dispersed-growth aeration? What are its advantages and disadvantages?
7. What is meant by "trickling filtration" and when would you use it in preference to biological aeration?
8. Is spray irrigation a suitable method of disposing of dissolved organic matter?
9. Can you use subsurface disposal for dissolved organic solids? When?
10. What is the theory of the Bio-Disc treatment system? Does it resemble trickling filtration or activated-sludge treatment?
11. What methods are used for nonbiological oxidation of dissolved organic wastes? Explain the principles of ozonation, chlorination, pure oxygen, and photolysis treatments.
12. What is wastewater scavenging and what are its limitations?
13. Describe how chemical oxidation can be used to destroy organic matter. What chemicals are employed in this method? What special properties make these chemicals applicable to destruction of organic matter?

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