

CHAPTER 9

Treatment and Disposal of Sludge Solids

Of prime importance in the treatment of all liquid wastes is the removal of solids, both suspended and dissolved. Once these solids are removed from the liquids, however, their disposal becomes a major problem. Unfortunately, waste engineers spend more time and money removing the solids than finally treating and disposing of them, so often a poor solids-disposal program will cause trouble in an otherwise properly designed and operated waste-treatment plant. When the solids-disposal system is poor, the solids tend to build up in the flow-through treatment units, and overall removal efficiencies then begin to decrease. Therefore, proper sludge handling enhances the overall treatment of all wastes. The following list contains most of the methods commonly used to deal with sludge solids: (1) anaerobic and aerobic digestion; (2) vacuum filtration; (3) elutriation; (4) drying beds; (5) sludge lagooning; (6) wet combustion; (7) atomized suspension; (8) drying and incineration; (9) centrifuging; (10) sludge barging; (11) landfill; (12) transporting to an acceptable landfill; and (13) miscellaneous methods.

Anaerobic and Aerobic Digestion

Anaerobic digestion is a common method of readying sludge solids for final disposal. All solids settled out in primary, secondary, or other basins are pumped to an enclosed airtight digester, where they decompose in an anaerobic environment. The rate of their decomposition depends primarily on proper seeding, pH, character of the solids, temperature, and degree of mixing of raw solids with actively digesting seed material. Digestion serves the dual purpose of rendering the sludge solids readily drainable and converting a portion of the organic matter to gaseous end-products. It may reduce the volume of sludge by as much as 50% organic matter reduction. After digestion, the sludge is dried and/or burned or used for fertilizer or landfill.

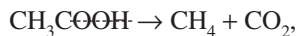
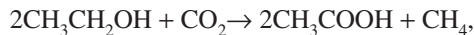
Two main groups of microorganisms, hydrolytic and methane, carry out digestion. Hydrolytic bacteria exist in great numbers in sewage and waste sludges and are capable of rapid rates of reproduction; they are saprophytic microorganisms that attack complex organic substances and convert them to simple organic compounds. Among these saprophytes are many acid-forming bacteria that produce fatty acids of low molecular weight, such as acetic and butyric, during degradation processes. In some cases, such acids are produced in quantities sufficient to lower the pH to a level at which all biological activity is arrested.

Fortunately, methane bacteria, the other group of microorganisms, are capable of using the acid and other end-products formed by the hydrolytic bacteria. Methane producers, however, are sensitive to pH changes and proliferate only within a narrow pH range of 6.5–8.0, with an optimum of 7.2–7.4; furthermore, they are few in number and reproduce slowly. Consequently, organic acids may form faster than they can be assimilated by the limited population of methane bacteria. As a result, the pH may be lowered and conditions made even more unfavorable for methane bacteria. When this happens, lime is usually added and the digestion process stopped until normal conditions return.

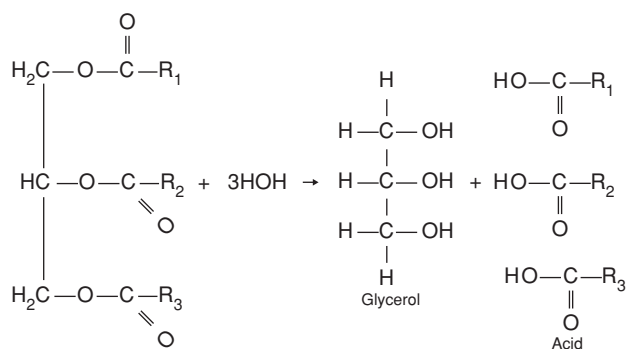
The proper environment for both types of bacteria requires a balance among the population of organisms, food supply, temperature, pH, and food accessibility. The following factors are measures of the effectiveness of digestive action: gas production (both quantity and quality), solids balance (total, volatile, and fixed), biochemical oxygen demand (BOD), acidity and pH, volatile acids, grease, sludge characteristics, and odor.

As mentioned earlier, fermentation (digestion) of organic matter proceeds in two stages: (1) hydrolytic action that converts organic matter to low-molecular-weight organic acids and alcohols, and (2) evolution of carbon dioxide and the simultaneous reduction to methane (carbon dioxide is actually consumed). The following general equations represent the digestion of carbohydrates, fats, and proteins:

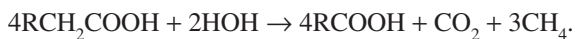
Carbohydrates:



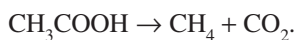
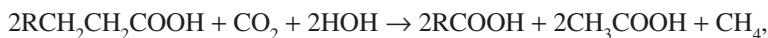
Fats:



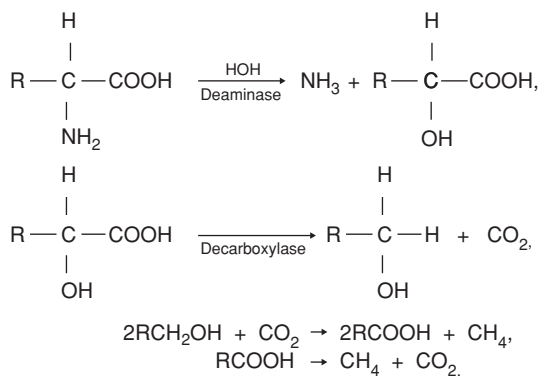
Alpha oxidation of acids:



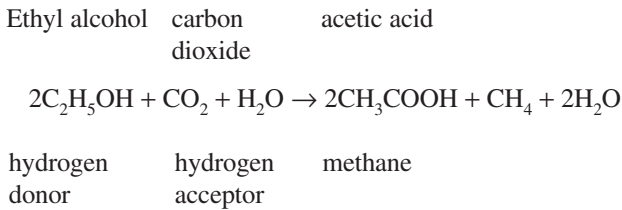
Beta oxidation of acids:



Proteins:



One hypothesis is that each molecule of methane arises from a reduction of one molecule of carbon dioxide. In other words, carbon dioxide acts as the hydrogen acceptor, while the alcohol acts as the hydrogen donor, as in the following equation:



One can readily see that carbon dioxide is an important food constituent. In mixed cultures, carbon dioxide is produced by other organisms, and therefore becomes more available than sulfates or nitrates. Buswell and Hatfield (1939) described fermentation as a chain of reactions involving the transfer of hydrogen.

The slowest reaction in the degradation process, production of methane, is therefore the rate-controlling reaction. The essential physiological characteristics of methane bacteria follow: (1) they are obligate anaerobes; (2) they require carbon dioxide as a hydrogen acceptor; (3) as hydrogen donors, they use simple organic substances, such as calcium acetate, butyrate, and ethyl and butyl alcohols; (4) their nitrogen source is ammonia; (5) they develop at a slow rate because of low energy yields; (6) they do not form spores; and (7) they are very sensitive to changes in pH.

Buswell and Hatfield (1939) concluded that the higher the percentage of carbon atoms in the fatty acid substrate, the higher the percentage of methane in the gas. Barker (1936a,b, 1937) established the following unique features of methane fermentation:

1. It takes place in mixed or enriched cultures, and hence may be maintained continuously on a large scale.
2. It is applicable to any type of substrate except lignin and mineral oil.
3. The reaction is quantitative and converts the entire substrate to carbon dioxide and methane.
4. There is no specific temperature limitation in the range of 0–55°C, but once the culture has been acclimated to a certain temperature, a drop of 2°C may completely interrupt methane fermentation and render obstructive the accumulated acids.
5. The presence of inert solid matter is important, and thus the addition of straw or sawdust to industrial wastes may be required.
6. If the substrate concentration is too great, volatile acids build up and inhibit the fermentation, especially when their buildup occurs faster than their subsequent conversion to methane. Keeping the volatile acid level below 3,000 ppm and closer to 2,000 helps the situation, but alkali addition will not alleviate it because it is not a pH effect. Mineral salts begin to inhibit the fermentation at 4,000 ppm, and 50 ppm of nitrate nitrogen inhibit it completely.

The extent of reduction of volatile solids by digestion depends in part on the amount of volatile matter in the raw sludge. Schlenz (1937) found that when volatile

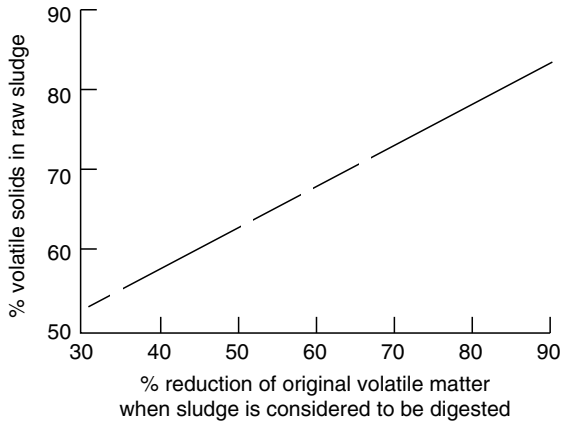


FIGURE 9.1. Reduction of volatile matter in raw sludge by digestion (from Ontario Water Resources Commission 1964).

solids in raw sludge increased from 55 to 80%, the reduction in volatile matter increased from 35 to 85%. This is shown graphically in Figure 9.1.

The usual unit-capacity requirements may be reduced, provided the operations are controlled and carried out as follows (Federation of Sewage and Industrial Waste Association 1959): (1) tank contents must be agitated to maintain an even mixture of raw and digesting solids; (2) raw sludge must be added continuously to the digestion unit; and (3) raw sludge must be concentrated or prethickened before being added to the digester. Two-stage digestion, with the first stage used primarily for active digestion and the second stage for storage and sludge consolidation, is often performed in two separate tanks. It is usually more economical in large plants with continuous operation.

With some industrial sludge wastes, it may be possible and economically feasible to either reuse the methane gas for heat/power or produce sufficient hydrogen gas (by modified digestion) to serve as an alternative fuel for automobiles. During the first stage of anaerobic digestion—where hydrolysis of the organic matter occurs primarily—hydrogen may be more prevalent than methane, while during the final stage of digestion, methane may be a primary source of additional energy.

Aerobic digestion is now playing an important role in small plants. It is claimed that less-skilled operators are required; also, air is normally available in these plants because secondary treatment of the liquid-waste fraction is becoming rather commonplace (Eckenfelder 1956).

Vacuum Filtration

“Vacuum filtration” is a means of de-watering sludge solids, and has become popular because the volume of solids for ultimate disposal is reduced and the sludge is drier than it would otherwise be, thereby improving “handleability.” Large plants are

increasing their use of vacuum filtration. Some plants filter chemically precipitated and/or plain settled sludge, while others filter digested sludge. In a typical vacuum-filtration unit, a porous cylinder overlying a series of cells revolves about its axis with a peripheral speed somewhat less than 1 ft/min, its lower portion passing through a trough containing the sludge to be dried. A vacuum inside the cylinder picks up a layer of sludge as the filter surface passes through the trough, and this increases the vacuum. When the cylinder has completed three-quarters of a revolution, a slight air pressure is produced on the appropriate cells, which aids the scraper, or strings, to dislodge the sludge in a thin layer. Sometimes it is necessary to add chemicals, such as lime and ferric chloride, as sludge conditioners before filtration. Filtering rates should be from 2 to 10 lb of dry solids per square foot per hour. Vacuum filters are available in diameters up to about 20 ft and in many lengths.

The quality of the filter medium (the material covering the cylinder) is important in the performance and life of the filter. In the past, woven-fabric filter media have been widely used. The physical process of solids retention on woven filters is a combination of at least three actions: (1) straining action, in which particles larger than the filter-medium openings cling to the filter; (2) adsorption, or attraction, to the filter of particles smaller than the openings in the filter medium; and (3) filtration of particles of different sizes that cling to already filtered caked material. The first two actions prevail at the onset of filtration, but as the "cake" builds up, the third is responsible for the greatest amount of solids removal. Thus, the problem arises that unless the cake is removed completely and the fiber filter medium kept clean continually, the filter will clog or "blind."

Tiller and Huang (1951) reported that there is a paucity of theory and research on filtration through porous media. Three reasons for this deficiency are (1) complexity of vacuum-filtration machinery, (2) difficulty of experimentally reproducing the precipitates found in filter beds, and (3) insufficient interest on the part of researchers. They also reported that although flow through the filter beds is almost always viscous, no reliable theory has been developed on the relation between permeability and porosity of the filter medium as affected by compressive pressure.

A major step toward lengthening the life and decreasing the operation problems of vacuum-filtration systems is the use of stainless-steel coil-spring filter media. A representative unit of this type, the Coilfilter, is shown in Figure 9.2 (Komline-Sanderson Engineering Corp.).

Elutriation

"Elutriation" is a process of improving filtration by washing the sludge. It reduces the alkalinity and, therefore, the lime coagulant demand of sludge by upgrading the biochemical quality of the sludge water before chemicals are added (Genter 1956). There are three practical methods of washing sludge solids; the equipment used in all cases is relatively simple, with upward-flow tanks frequently used.

1. Single-stage elutriation, which involves one batch at a time, is a fill-and-draw procedure; sedimentation and decantation are performed in a single step.

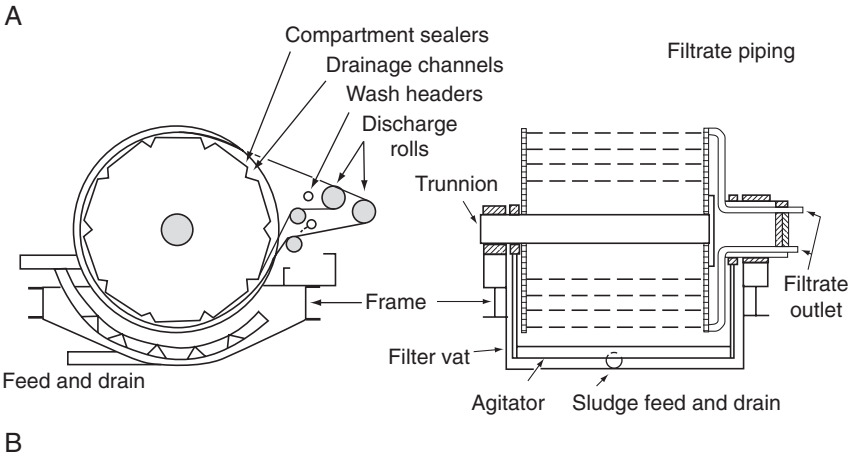
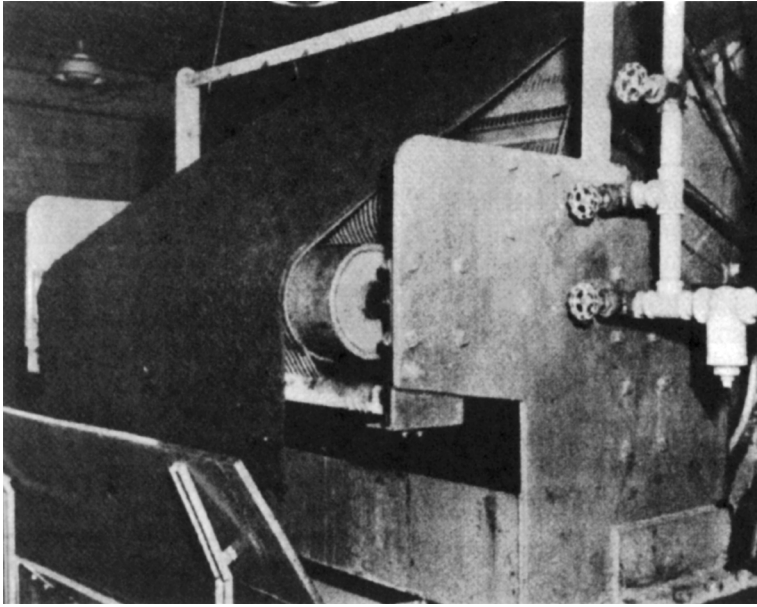


FIGURE 9.2. (A) The Coilfilter, a patented machine for the vacuum filtration of sludge. This particular machine, in use since 1953 at the sewage-treatment plant at St. Charles, Illinois, has filtering media made up of two layers of alloy steel coiled springs, each spring made endless by joining its two ends with a threaded plug. These springs discharge the filter cake after each revolution of the cylinder and are then washed before they reenter the vat for another cycle. The material at the left, which looks like a length of corduroy, is actually a layer of sludge (adapted from Komline-Sanderson Engineering Corp.) (B) Schematic drawing of the Coilfilter shown in (a) (courtesy Komline-Sanderson Engineering Corp.).

2. Two-stage elutriation involves repeating the single-stage steps on the elutriated sludge, using freshwater on the second wash. In small plants, the same settling tank may be used for both stages.
3. In larger plants (6,000–24,000 lb of solids per day), a second tank, connected in series with the first, is usually employed. Such a two-tank system can also be used for countercurrent washing. With this system, the freshwater is added only to the second-stage washing, and the decanted elutriate (or top water) from this tank flows by gravity to mix with the sludge entering the first tank.

Because the degree of chemical fouling (Genter 1946) resulting from digestion can be conveniently measured in terms of alkalinity, an elutriated sludge can be defined as one that has had the alkalinity of its water reduced by dilution with water of lower alkalinity, sedimentation, and decantation. Advantages of elutriation as a preliminary to sludge de-watering on vacuum filters include elimination of ammonia odors and of the need to use lime in sludge conditioning. Elutriation may also reduce the capacity requirements of secondary digesters (used for storage and additional digestion to ensure optimum filtration), and it is particularly helpful in that it permits small plants to use vacuum filters to advantage. Genter (1946) claimed that elutriation reduces the ratio of sludge water to the mineralized sludge solids; thus, there is a marked decrease in the chemicals required for conditioning. The savings in ferric chloride are illustrated in Figure 9.3, which is based on data from Genter (1946).

Genter (1956) also discusses a method of predicting the final alkalinity of elutriated sludge by a formula. Assuming that a equals the volumes of pure water added to one volume of fouled sludge mixture, he obtains the following relationships:

$a + 1 =$ total volume of mixed sludge and clean water.

$1/(a+1) =$ fraction of original concentration of fouling agent left if solids are allowed to settle back to a washed-sludge equivalent to the original volume and the added volume of water is siphoned off.

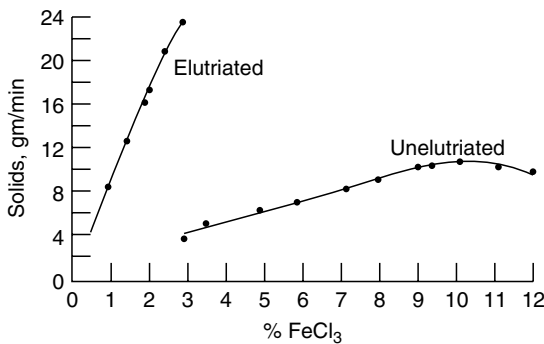


FIGURE 9.3. Effect of elutriation on FeCl₃ required for conditioning of sludge.

$1/(a+1)^2$ = fraction of original concentration of fouling agent if this same dilution, sedimentation, and decantation technique is repeated.

Therefore, the fraction of original fouling agent left in the final sludge is $1/(a^2+2a+1)$ if the second wash water is decanted for a new first wash and the two elutriation tanks are placed on countercurrent series. For example, if four volumes of pure water are used to wash a digested sludge of 3,000-ppm alkalinity, the alkalinity left in the elutriated sludge after countercurrent washing in two tanks is

$$(3,000) / [(4)^2 + (2 \times 4) + 1] = 120 \text{ ppm.}$$

Drying Beds

Sludge-drying beds remove moisture from sludge, thereby decreasing its volume and changing its physicochemical characteristics so that sludge containing 25% solids can be moved with a shovel or garden fork and transported in watertight containers.

Sludge filter beds are made up of 12–24 in. of coarse sand, well-seasoned cinders, or even washed grit from nearby grit chambers and about 12 in. of coarse gravel beneath the sand. The upper 3 in. of gravel particles are 1/8 to 1/4 in. in diameter. Below the gravel, the earth floor of the bed is pitched to a slight grade into open-joint tile underdrains 6 or 8 in. in diameter. These tiles may be laid from 4 to 20 ft apart on centers, depending on the porosity of the coarse gravel. Disposing of the underdrain liquor sometimes poses a problem; this should never be discharged without an analysis of its constituents and usually some form of treatment. Several smaller rectangular beds serve the purpose better than one large filter bed. These beds may be covered with glass or plexiglas when weather conditions demand, in which case ventilation must be provided to dissipate the hot wet air above the beds.

Generally speaking, raw settled sludge does not drain well on sand-drying beds. Some form of pretreatment—digestion, elutriation, and/or chemical treatment—is usually required. Well-digested sewage sludge will de-water more readily than partly digested sludge (American Society of Civil Engineers 1959). However, prolonged storage of digested sludges decreases drainability because the gases present initially permit more drainage of moisture through the filtering medium, thus reducing the evaporation cycle. A high total solids content in digested sludges naturally permits greater removal of dry solids per year from sludge beds.

Drying time is dependent on climate and dosing depth, 8 in. being generally accepted as most desirable for rapid drying. It is, naturally, short in regions of plentiful sunshine, scant rainfall, and low relative humidity, such as certain arid areas of the South where summers are long. Wind velocity also affects speed of sludge drying on the beds. In fact, all the factors enhancing evaporation will also aid in drying sludge. Cox (1940) derived the following equation for calculating the rate of evaporation of water, which may also apply to sludge-drying, although exact values of constants may vary from water to sludge water:

$$E = (e_a - e_d + 0.0016 \Delta T) / (0.564 + 0.051 \Delta T + W/300),$$

where

E = evaporation (in./day)
 e_a = saturated vapor pressure at air temperature
 e_d = actual vapor pressure
 ΔT = difference between mean temperature of the air and that of the water
 W = velocity of the wind (miles/day).

Meyer's formulation is also widely used:

$$E = C (V - v) (1 + W/10),$$

where

E = evaporation (inches) for a given unit of time
 V = saturation vapor pressure at the water temperature (inches of mercury)
 v = actual vapor pressure of the air, 25 ft above ground
 W = wind velocity (mph), 25 ft above ground
 C = coefficient, varying with unit of time used and depth of water (varies from 0.36 to 0.50).

In addition to evaporation, the drying rate is also influenced by capillary action, which causes water to rise from the depths of the sludge to the evaporative surface.

In the case of domestic-sewage sludge, engineers estimate that approximately 20–25 lb of dry solids can be loaded onto 1 ft² of properly designed sand-base drying bed each year. Haseltine (1951) takes exception to this unit-of-loading estimate and suggests a "gross bed loading," which takes into account the number of pounds of solids applied per square foot per 30 days of actual bed use. For example, if sludge that has a density of 62.5 lb/ft³ and contains 10% solids is applied 12 in. deep and removed after 40 days, the gross bed loading is

$$(62.5 \times 0.10 \times 30) / (40) = 4.69 \text{ lb/ft}^2/30 \text{ days.}^1$$

Haseltine (1951) also develops the following straight-line relationship between the gross bed loading (Y) and the percentage of solids in applied sludge (X) from data supplied by 14 plants for periods of operation up to 14 years:

$$Y = 0.96X - 1.75$$

The gross bed loading Y varied from 0 to 10 and X varied from 0 to 14. He concluded that, after temperature, the solids content of the sludge in drying beds is the

¹ The specific gravity of wet sludge assumed is 1.0.

most important factor influencing bed performance. The amount of moisture to be removed from the sludge is the third most important factor.

Sludge Lagooning

“Lagoons” may be defined as natural or artificial earth basins used to receive sludge. Lagooning is practiced when the economics of the situation (money and land) indicate its use, because it is a relatively inexpensive method of treating waste sludges. However, there are many other factors to be considered: (1) nature and topography of the disposal area; (2) proximity of the site to populated areas; (3) meteorological conditions, especially whether prevailing winds blow toward or away from populated areas; (4) soil conditions; (5) chemical composition of sludges, with special consideration given to toxicity and odor-producing constituents; (6) proximity to surface-water or groundwater supplies; (7) effect of waste materials on the porosity of the soil; (8) means of draining off the supernatant to provide more space in the lagoon; (9) fencing and other safety measures when lagoons are deeper than 5 ft; and (10) nuisances, such as weed growth, odors, and insect breeding.

Lagooning of wastes in limestone areas is particularly hazardous because of the channels and cavities found underground in these formations (Powell 1954). Ordinarily groundwater moves slowly, sometimes less than 1 ft/day, depending on the fineness of the aquiferous sand through which it percolates and the degree of saturation of the sand. In limestone country, water may travel vertically and laterally at much higher velocities, so that sludge lagooned on high ground may quickly contaminate large portions of valuable groundwater supplies. Manufacturing plants often bulldoze out a sludge lagoon every year or two, the frequency depending on sludge buildup and soil conditions.

Bloodgood (1946) stated that at least 1 lb of raw sewage solids can be digested per year per 0.17 ft³ of lagoon capacity. However, if lagoons are to be used for both digestion and de-watering, 1 lb of raw-sludge solids requires about 0.4 ft³/yr of lagoon capacity, provided that air-dried sludge is removed as soon as it becomes ready for hauling.

Wet Combustion Process

The Zimpro process is a relatively innovative treatment for sludge. It operates on the basic principles that (1) organic matter contained in an aqueous solution can be oxidized, and whatever heat value it contains released, and (2) oxidation at this stage is more effective than if the water were first evaporated and the residue used as fuel in a conventional boiler. Because heat is liberated by a fuel only when it is subjected to combustion in the presence of air, the Zimpro process depends on air being forced into a reactor vessel. One objective of this process is the production of the maximum number of Btu's from the organic matter in a waste effluent per pound of compressed air fed into the reactor.

Because the Zimpro process eliminates conventional filters, chemicals, sludge-digestion units, incinerators, and auxiliary equipment, it reduces space and land requirements. The end-products are steam, nitrogen, CO₂, and ash. The effluent gases

from the reactor, having been “scrubbed” with water, contain no fly ash and are practically odorless.

In the treatment of sewage sludge, oxidation is brought about by continuously pumping the sludge and a proportionate amount of air (both sludge and air at elevated temperatures and pressures) into a reactor vessel. Combustion occurs as the oxygen in the compressed air combines with the organic matter in the sludge to form CO_2 , N_2 , and steam, while the ash remains in the residual water. The reactor, and the whole process system, is automatically maintained at a constant pressure and the products of the combustion are continuously removed from the reactor. If the concentration of volatile matter is high and the sewage sludge concentration is great enough (>5%), the steam, plus the gases (CO_2 and N_2), which are products of combustion, will contain more than enough energy to run the air compressors and pumps used in the process. The residual hot water from the reactors is used in heat exchangers that raise the temperature of the incoming sludge and air sufficiently to cause oxidation to begin as soon as they come together in the reactor. In this way, once the process is started, no external heat or power is required to sustain the combustion.

Equipment required for the Zimpro process includes: compressor, air receiver, high-pressure sludge pump, sludge-storage tank with agitators, heat exchangers, reactor, separator, and cooler. A schematic drawing of the process is presented in

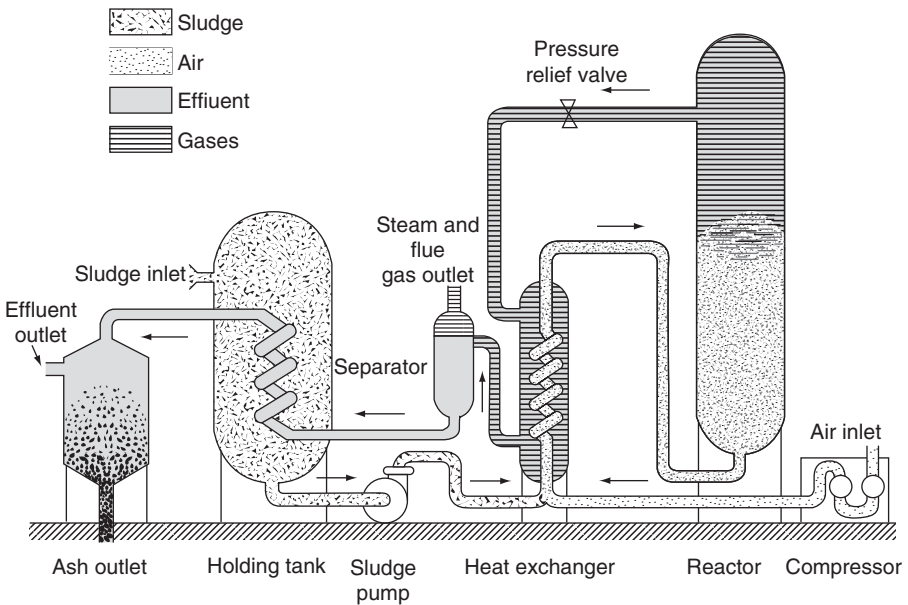


FIGURE 9.4. Schematic diagram of the Zimpro process for sewage-sludge oxidation (courtesy Sterling Drug Co.).

Figure 9.4. The manufacturer (New Zimpro Sludge Oxidation Units for Smaller Communities, Sterling Drug Co., Rothschild, Wisconsin) claimed that

Units achieve 80 to 90% reduction of insoluble organic content of sewage sludge by oxidation without flame. Sludge is burned without de-watering or pretreating. The unit operates continuously at pressures of 500 to 600 psig and temperatures of 420°F. End products are substantially inorganic, inert, biologically stable ash; residual water; and odor-free gaseous products of combustion (carbon dioxide, nitrogen, and steam). The plant is designed for automatic operation with minimal maintenance. An air compressor and sludge pump are the only equipment components with moving parts. Power requirement is approximately 50 hp for a one-ton unit (dry weight). Building and land-space requirements are nominal.

Teletzke (1965) described the low-pressure Zimpro treatment, which operates in the range of 150–300 psi at about 300°F. He portrayed low-pressure wet-air oxidation as an economical and flexible method of producing a sterile, drainable, and completely acceptable end-product for ultimate disposal.

Atomized Suspension

The atomized-suspension technique consists of atomizing the waste liquor or slurry in the top of a tower, the walls of which are maintained at an elevated temperature by hot gases circulating through a jacket, a method described by Rabinovitch et al. (1956) and Gauvin (1957). No air, or other foreign gas, is introduced into the equipment, which sharply distinguishes this technique from spray drying. The developers claimed that in the immediate range of the nozzle, the finely divided droplets (20–25 mm in diameter) quickly decelerate from the high initial velocity and then become dispersed in the vapor produced by their own evaporation. The suspension thus created flows down the reactor in a nearly streamline motion. Evaporation, quickly completed, is followed by drying. At the end of the drying zone, dried particles can be subjected to a sequence of chemical reactions, such as oxidation, reduction, nitration, sulfonation, and so forth, through the injection of the proper internal gaseous reactants (in the presence of a powdered catalyst, if necessary). When it leaves the reactor at the bottom, the suspension consists of a solid residue (which is recovered in cyclone collectors), large amounts of steam (which is condensed and utilized), and by-product gases (which can be further processed for recovery or piped away for disposal).

Advocates of the atomized-suspension process claim that the only outside energy required is that used for pumping of the liquid, an almost negligible amount. A striking feature of the recovery flow sheet is the complete absence of blowers or compressors, although large volumes of gases and vapors are continuously flowing through the

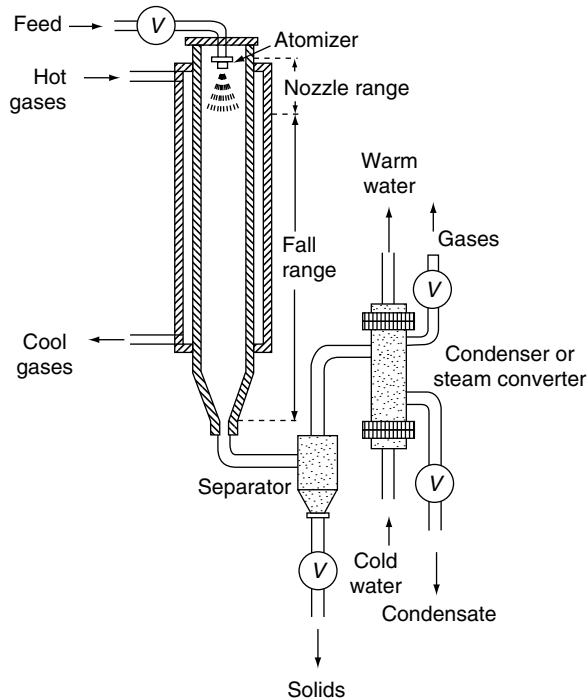


FIGURE 9.5. Apparatus for the atomized-suspension technique (adapted from Gauvin 1957 and Rabinovitch et al. 1956).

system. Need for them is eliminated by the efficient utilization of the pressure generated in the reactor during evaporation. A typical flow sheet for this process (Rabinovitch et al. 1956; Gauvin 1957) is shown in Figure 9.5.

Drying and Incineration

A large volume of sludge can be reduced to a small volume of ash, which is free from organic matter and, therefore, easily disposable, by a combination of heat drying and incineration (Dorr Co. 1941). Flash drying involves drying sludge particles in suspension in a stream of hot gases, which ensures practically instantaneous removal of moisture. When hot gases created by the drying and oxidation of the sludge itself are used directly for drying, there are no conversion losses. After the flash-drying, the gas containing sludge particles usually passes to cyclone separators, where the dried sludge is separated from the moisture-carrying cooler gases.

Flash-dried sludge is used as fertilizer, soil conditioner, or for other valuable purposes. Unused dried sludge can be incinerated by blowing it through a duct to a burner in the combustion chamber of a furnace. The sludge blower, in addition to conveying the sludge to the furnace, also supplies the major portion of the air required for combustion. To eliminate odors, preheated gases after combustion are returned to

the combusting sludge. To eliminate fly ash, the cooled gas after combustion is drawn through an ash collector by induced-draft fans, and the fly ash settles out by centrifugal action and is discharged automatically into the furnace bottom. This ash can be removed from time to time, either by shoveling or by mixing it with water and pumping it out to be used as landfill.

Whether the ultimate aim is to dry the sludge for use as a soil additive or to incinerate it to a sterile ash, it is necessary first to evaporate the free moisture from the solids, remove it in the form of a gas, and discharge it to the atmosphere. This gas is referred to as the *evaporator load*. Only high-temperature (1,200–1,400°F) deodorization is effective in controlling odors from sludge incinerators.

When sludge is to be incinerated, the heat released in the furnace is also important; the furnace volume should be ample to allow a heat release of X Btu/ft³ of furnace (generally held at 12,000 Btu/ft³ of furnace volume per hour to ensure long life of walls and furnace). The heat input is determined by multiplying the pounds of dry solids to be incinerated per hour by the gaseous products of the volatile-solids content and their heat value. The furnace volume required can, therefore, be computed by dividing this heat input by 12,000. Thermal efficiencies of 30–60% can be expected from incinerators. The lower the stack temperature, the higher the thermal efficiency (Leet et al. 1959). This relationship is shown in Figure 9.6. In Figure 9.7, a flow diagram is presented (Leet et al. 1959) to show heat balance for a flash-drying and incineration system.

To calculate the rate of drying during the constant-rate period (after the temperature of the material adjusts itself to the drying conditions), either the mass-transfer or the heat-transfer equation may be used (McCabe and Smith 1956):

$$\text{(mass transfer)} \quad W = k'_y(H_i - H)A;$$

$$\text{(heat transfer)} \quad W = [h_y(t - t_i)A]/\lambda_i,$$

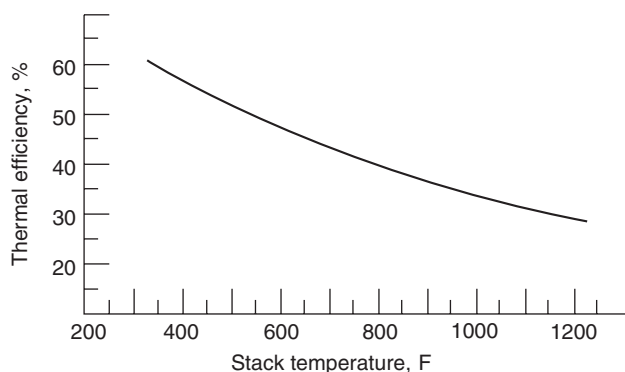


FIGURE 9.6. Effect of stack temperature on thermal efficiency (adapted from Leet et al. 1959).

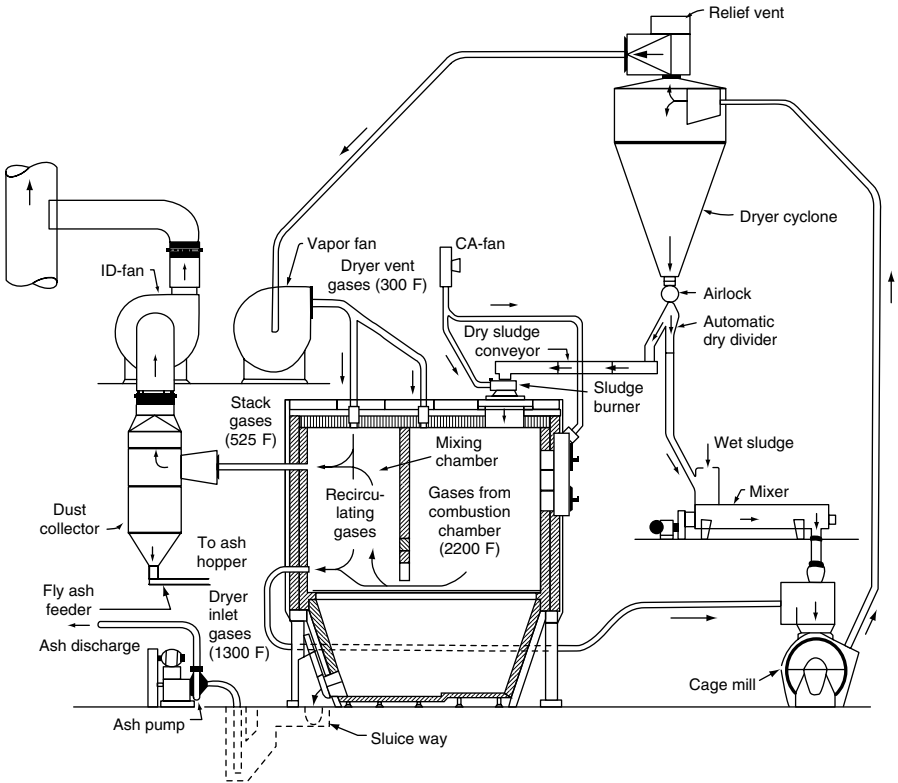


FIGURE 9.7. Flow diagram for heat balance for a flash-drying and incineration system (Leet et al. 1959).

where

- W = evaporation rate (lb/hr)
- A = drying area (ft²)
- h_v = heat-transfer coefficient (Btu/ft²/hr/°F)
- k_y = mass-transfer coefficient (lb/ft²/hr for a unit of humidity difference)
- H_i = humidity of air at interface (lb water/lb dry air)
- H = humidity of air (lb water/lb dry air)
- t = temperature of air (°F)
- t_i = temperature at interface (°F)
- λ_i = latent heat at temperature t_i (Btu/lb).

The heat-transfer coefficient, h_v , is estimated to be about $0.128 G^{0.8}$ when air flows parallel to the sludge surface and about $0.37 G^{0.37}$ when air flows perpendicular to the sludge surface (G = the mass velocity in lb/ft²/hr).

Pit incineration has been used to dispose of certain solid and semisolid wastes. The incinerator consists of a rectangular pit lined with firebrick, to which air is supplied to

retain particulates and to allow complete combustion. This disposal method is simple in concept and operation and is especially adaptable to situations in which the waste requires batch incineration. It has been used for disposal of synthetic organics and has been studied for disposal of paint sludges in the automotive industry (Balden 1967).

Dunn (1975) proclaimed that it was no longer a question of “shall we dump or shall we burn?” but “can we reclaim a product or recover waste heat from the waste?” He recommends a temperature in excess of 1,470°F (800°C) to oxidize carbon particles and 1,650–2,190°F (900–1,200°C) to remove odors from incinerator flue gas. Whether you burn solids, liquids, gases, or sludges, it is necessary to ascertain (1) the daily volume and weight, (2) whether wastes are batch or continuous, (3) what collection methods are used, (4) what methods of feeding the incinerator are required, (5) what the intended daily firing period is, and (6) whether waste heat recovery is required (or used elsewhere in the plant). Dunn (1975) acknowledged that submerged combustors were used to successfully recover HCl. When the price of caustic soda rises, this method of combustion becomes useful for the disposal of large quantities of chlorinated hydrocarbons (Santoleri 1972). Dunn (1975) also pointed out the increasing number of centralized incinerator disposal facilities in Europe because of the need for control over the handling and disposal of wastes.

Centrifuging

“Centrifuging” is a method of concentrating sludge to enhance final disposal. One of the factors that made centrifugal concentration unacceptable in the earlier installations was its low efficiency; large amounts of fine particles were returned to the system with the supposedly clarified effluent. Newer installations (Bradney and Bragstad 1955), using 20-hp built-in drive motors, can handle 3,000–4,000 gallons/hr of waste sludge, containing 0.5–0.75% solids on a dry basis. Only 11 hp are required once the centrifuge reaches operating speed (6,100 rpm). The resulting sludge is concentrated to about 5% solids and the effluent contains about 300 ppm solids. The centrifugal force throws the denser solid material to the wall of the centrifuge bowl, where it is discharged through nozzles located in the periphery. One bowl (Bradney and Bragstad 1955) is equipped with 12 nozzle openings, so that various numbers of discharge nozzles can be used depending on the amount of solids in the feed liquor and the results desired. Use of the centrifuge for higher concentrations is limited by the capability of the pumps, which discharge concentrated sludge from the centrifuges. The effluent from which the solids are separated travels toward the center of the centrifuge bowl through intermediate discs; as it discharges from the upper cover, it is claimed to average approximately 300 ppm solids. Centrifuged sludge is discharged from the lower cover of the centrifuge into a sump, from which it can be pumped to a digester or other final sludge-treatment units. Figure 9.8 is a schematic diagram of a centrifuge bowl. Blosser and Caron (1965) expect the costs of centrifuging paper-mill sludges to vary from \$4 to \$20 per ton of dry solids, including the hauling of the cake.

Ambler (1961) reviewed the theory of centrifugation. When a force is applied to a particle, the particle is accelerated ($F = ma$) until it reaches a velocity along the line of the force at which the resistance to its motion equals the applied force. In a settling tank, this

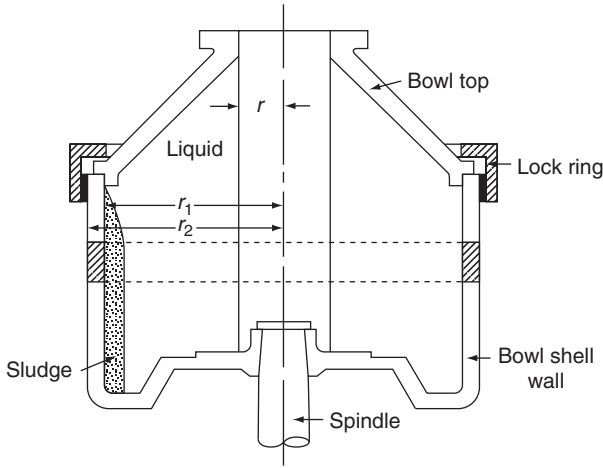


FIGURE 9.8. Centrifuge bowl schematic.

is the force of gravity. In a centrifuge, it is the centrifugal field, w^2r . The two differ only in direction and order of magnitude. The gravitational field is along a radius normal to the axis of rotation and may be upward of 60,000 times that of gravity for continuous-flow centrifuges. The velocities of particle movements are generally proportional to the square root of the diameter of the particle. The effective force acting on the particle is

$$F = (m - m_l)w^2r,$$

and for a sphere, it is

$$F = \pi/6(d^3) \Delta p w^2 r.$$

The force opposing sedimentation, according to Newton's draw law in laminar flow, is

$$F = 3\pi\mu d.$$

At equilibrium (Stokes' law),

$$v_s = [\Delta p d^2 (w^2)r] / 18\mu.$$

In the simplest form of a continuous centrifuge, v_s is the velocity with which the particle, if it is heavier than the fluid, approaches the bowl wall. If X is the distance the particle will travel,

$$X = t - [\Delta p d^2(w^2)r(V)] / 18\mu Q$$

If X is greater than the initial distance and the given particle is from the wall of the rotor, the particle will be deposited against the wall and be removed from the system. In an ideal system ($X = s/2$), half the particles of diameter d will be removed. This may be considered the cutoff point at which

$$Q = (\Delta p d^2 / 9\mu) \cdot (V w^2 r / s),$$

where Q is volume of flow per unit of time.

Because the term $\Delta p d^2 / 9\mu$ is concerned only with the parameters of the system that follow Stokes' law and the term $V(w^2)r/s$ with the parameters of the rotor, the previous equation may be written as

$$Q = 2Vg\Sigma$$

in which

$$Vg = [\Delta p(d^2)g] / 18\mu \text{ and } \Sigma = [V(w^2)r\theta] / gs\theta,$$

where $r\theta$ and $s\theta$ are the effective radius and settling distance, respectively, of the centrifuge, and Σ is an index of centrifuge size that has the dimension of (length)² and is the equivalent area of a settling tank theoretically capable of doing the same amount of useful work as the centrifuge.

Ambler (1961) used the previous theory to formulate an index of centrifuge sizes for various centrifuge types as follows:

1. For the laboratory test-tube or bottle centrifuge,

$$\Sigma = (w^2)V/4.6 \log [2r^2/(r_1 - r_2)].$$

2. For the tubular-bowl centrifuge,

$$\Sigma = \frac{\pi / \omega^2 (r_2^2 - r_1^2)}{g \ln \left[2r_2^2 / (r_2^2 - r_1^2) \right]}.$$

3. For the disc-type centrifuge,

$$\Sigma = \frac{2\pi n\omega^2 (r_2^3 - r_1^3)}{3gC \tan \theta},$$

where

Σ = equivalent area of the centrifuge

w = angular velocity (rad/sec)

V = volume

- r = radius from axis of rotation
- r_1 = radius to inner surface
- r_2 = radius to outer surface
- l = light-phase discharge radius
- g = gravitational constant
- n = number of spaces between discs
- C = concentration of solute
- \emptyset = half-included angle of the disc.

In each of these cases, Ambler (1961) bases his calculations on the behavior of a single particle under conditions of unhindered settling and on the assumption that this particle is always in equilibrium with the force field of the centrifuge under the conditions defined by Stokes' law.

Sludge Barging

Sludge barging or ocean disposal is one of the means of final disposal of sludge that has been practiced by some cities. There is little theory involved in this method of treatment. Raw, precipitated, digested, or filtered sludge solids are pumped into a waiting barge and transported to a suitable site from the shore, where it is discharged, usually by pumping out deep under the water surface. There are some advantages of this method of disposal, such as relatively lower operating costs and reduced land demands. However, experience has shown that this method of disposal results in several environmental concerns: (1) long-term adverse effects on the ecology of the receiving water, (2) sludge floating matter rising to the surface, (3) public objection, and (4) potential for sludge residues carried to the shore during tidal cycles and causing public health impacts. Based on these concerns, this method of disposal has been discontinued and is not a recommended practice.

Sanitary Landfill

Sanitary landfill is used to bury garbage, refuse, and sludge in a planned and methodical manner (Salvato 1958). It is a relatively simple, effective, and inexpensive method for disposing of dry matter such as refuse, but sludge is usually too liquid for this procedure. However, mechanically de-watered or sand-bed-dried sludge can be disposed of in this matter.

The area proposed for the sanitary fill (Salvato 1958) should be easily accessible yet remote from sources of water supply and recreational areas while also being on land that is not too costly. The suitability of the soil and possible future use of the property are also important considerations.

For municipal refuse, the land area required is estimated at about 1 acre/yr for 10,000 persons, when using 6-ft-deep compaction. Sanitary landfills should be located above the groundwater level and no closer than 500 ft to any sources of water supply, particularly when the soil is sandy, gravelly, or of limestone derivation. The area should be staked out for trenches and benchmarks established, giving the elevation to which

the finished fill is to be carried and the depth to which excavations are to be dug. Normally a trench is about 15 ft wide and about 4 ft deep. At the end of each day's dumping, the sludge should be covered and compacted by a bulldozer or tractor. Bacon (1967) suggested using sludge to reclaim land as an economic method of disposal, especially in marginal lands and coal strip-mining areas.

One of the major concerns for sludge disposal in a landfill is the presence of hazardous or toxic constituents in the sludge. Depending on the type of constituents, the soil type underlying the landfill, and the depth to groundwater, these constituents could leach out of the landfill and migrate and contaminate the groundwater. Heavy metals, precipitated during the industrial wastewater treatment, are some of the commonly found toxic constituents in sludge. Other toxic organics including petroleum-based and other chlorinated solvents could also be present in the sludge. Recently promulgated hazardous waste regulations by the Environmental Protection Agency (EPA) on land ban of hazardous chemicals have restricted the disposal of industrial wastes in landfills. In the context of these regulations, it is important to determine whether the constituents present in the sludge are banned from landfill disposal and whether the sludge is considered a hazardous waste based on special characteristic criteria specified by the EPA such as ignitability, corrosivity, reactivity, and leaching tests (EP Toxicity or TCLP) before deciding on the landfill-disposal option. Also, because of long-term potential liabilities of contaminating the groundwater, it is difficult to find landfills off-site that will accept the industrial sludge. On-site landfills may be constructed after obtaining permits from local regulatory agencies. Generally, it is required and recommended that landfills be constructed with appropriate liners to prevent the migration of the leachate containing contaminants to the subsurface and groundwater. These issues are discussed in more detail in Chapter 11.

Transporting to Approved Landfills

Transporting sludges to approved landfills was used with greater frequency during the 1990s. The reasons for this change in usage include increased liability and cost of ultimate disposal by on-site treatment. Safe and suitable landfills are designed to prevent groundwater seepage and surface overflows. In addition, these landfills are operated to prevent the inclusion of industrial sludges that are potentially hazardous.

Under current Resource Conservation and Recovery Act (RCRA) practice, both the manifesting and the analysis of sludges have become more complete and, therefore, definitive. In addition, the ultimate cost of facility closure, monitoring, and, if it proves necessary, post-closure mitigation are factored in the operation cost base of the landfill.

Examples of these industrial sludges include precipitated ferric hydroxide from steel mills and machine water fines from paper mills.

Miscellaneous Methods

Other methods for disposing of sludge solids include sludge concentration, flotation, and thickening. Biological means, aided only by temperature and time controls, are used to induce flotation of sludges (Laboon 1952). The resultant solids, in concentrations of 20%, do not require the addition of chemicals when they are subsequently de-watered on

a vacuum filter. Optimum results with this method of concentration were found to exist at 35°C after a detention period of 120 hours (Laboon 1952). However, certain types of sludge (e.g., activated sludges) are not amenable to this treatment. Aside from time and temperature controls, the chief factors in the flotation method for concentration of raw sludges appear to be volatile content and pH.

In 1953 a method was developed by Torpey (1954) for thickening sludge on a continuous basis without the addition of chemicals. Generally, the flow pattern permits dilute sludge—from the primary clarifiers alone or combined with secondary sludge—to be fed to the center feedwell of a thickener. A schematic drawing of a typical thickener is shown in Figure 9.9. The solids settle, thicken in a definite “blanket” zone, and are drawn away from the bottom of the tank. The excess liquid is decanted by a peripheral weir. The thickeners also contain a mechanism with vertical pickets attached to the rake arms. The pickets are V shaped, and their channeling action allows entrapped water (water that is caught in sludge) and gases to escape to the surface. The degree to which the sludges can be thickened depends on several factors, the chief one being the source of the sludge (Brisbin 1956). The nature of the sludge is also most important. Some sludges are of a gelatinous and voluminous nature, which impedes thickening beyond a certain limit, regardless of detention time. Others are more granular and release

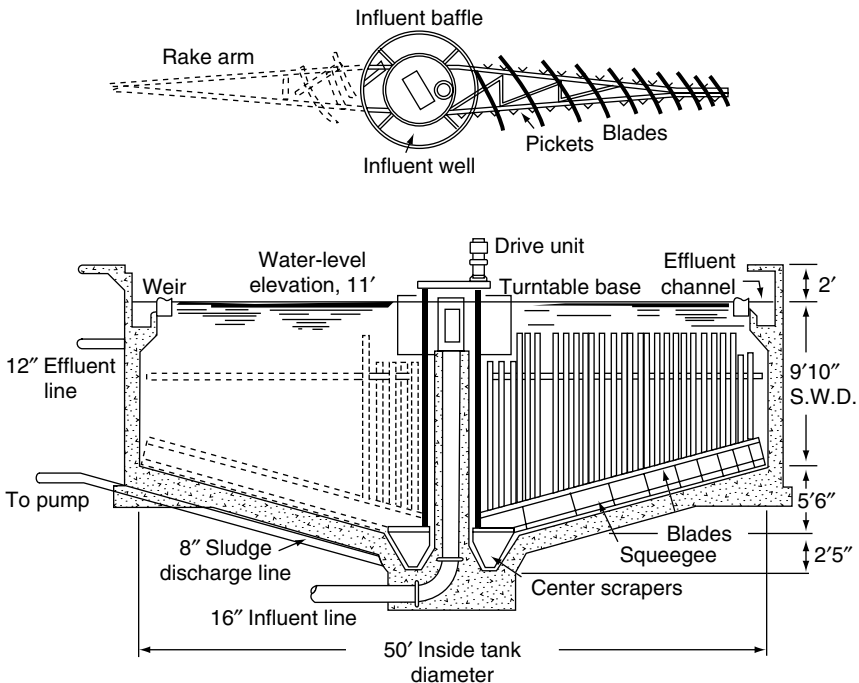


FIGURE 9.9. Schematic plan of thickener mechanism and section of tank (from Torpey 1954).

entrapped water when subjected to physical action, such as the slow mechanical mixing provided by the rotating pickets and rake arms.

Composting, a method of steeping solid wastes that contain 30–70% water in large piles and allowing microorganisms to decompose the organic fractions, has been used to some degree for solid wastes from industry. The process is accelerated when the piles are turned regularly by mechanical means. Mercer et al. (1962) found that the solid wastes of apricots and clingstone peaches were amenable to this form of treatment and that aerobic conditions were maintained by an initial daily turning for 5–6 days, followed by turning on alternate days until the process was complete.

The following includes six types of industrial sludges, along with their possible origin and more specific characteristics.

<i>Industrial Types</i>	<i>Sources</i>	<i>Character</i>
(1) Metal hydroxides	Plating Wastes	Cr(OH) ₃ Ni(OH) ₂ Zn(OH) ₂
(2) Organic residues	Paper mill Tannery Cannery Textile Winery Sugar refinery Poultry and meats	Fines Hair, skins, lime Pulp, seeds, skins, fruits, and vegetables Fibers Dregs Lees Feather, innards, fat
(3) Precipitated colloids	Steel mill Pickle liquor	Al(OH) ₃ Fe(OH) ₃
(4) Inorganic	Cement mill Steel mill	Sand Iron
(5) Alkaline or neutral residues	Fertilizers Sugar	Gypsum + impurities Steffans Sludge
(6) Organic residues from land use	Agriculture Crop debris Animal dung	Bagasse, corn Stalks, peanut hulls Cow, pig, sheep manure, duck and chicken droppings

Example of Twentieth-Century Practice of Sludge Solids Removal

Shimp et al. (2000) reported that operating experience is inadequate in the newer variations in anaerobic digestion. Therefore, much research remains to be done. They

recommended that managers of publicly owned treatment works considering any advanced digestion alternative should contemplate the following performance issues before deciding whether a particular system makes sense for their facility:

1. Class A pathogen reduction
2. Volatile solids destruction and gas production
3. Recycle nutrient loads, residual nutrients, and ammonia toxicity
4. Difficult-to-digest solids
5. Digester loadings and volume
6. Downstream de-watering
7. Residual odor
8. Implications for facility design, operations, and maintenance

Review Questions

1. Why is sludge treatment the most vital part of industrial-waste treatment?
2. How does anaerobic sludge digestion solve the problem of sludge treatment of industrial wastes?
3. How does it differ from aerobic sludge digestion? When would you use the latter rather than the former?
4. What factors influence the vacuum filterability of sludge?
5. How does elutriation aid in sludge treatment?
6. What are the principles and limitations of drying beds?
7. When would you recommend lagooning of waste sludge?
8. Under what conditions could a wet-combustion treatment be used for industrial-waste sludges?
9. What are the essential differences between Zimpro and atomized-suspension techniques for sludge treatment?
10. Discuss centrifuging as a sludge-concentrating process.
11. What are the advantages and disadvantages of sludge barging for ultimate disposal? How does this compare to sludge pumping into oceans as an ultimate disposal system?
12. Under what circumstances can you place industrial-waste sludges in a sanitary landfill?
13. What is the principle of sludge thickening and when is it used?

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