Chapter 5

VOLUME REDUCTION TECHNOLOGIES

INTRODUCTION

There are a wide range of technology options to select from for volume reduction purposes. These include incineration, size reduction, composting, concentrating techniques, and drying. Municipal solid waste disposal generally relies upon the first three, but industry often has unique applications and utilizes incineration, size reduction, concentrating methods, and drying more frequently. Among these technology groups, incineration (unless coupled with energy production), drying, size reduction, and concentrating techniques for the most part represent treatment practices. In other words, they are within the end-of-pipe category of options for waste management. They can be applied to incrementally improve environmental performance and achieve savings in operational costs for handling and disposing of large volumes of wastes, but they are not applied as source reduction methods. They can be effectively applied in pollution prevention and waste minimization projects as ancillary techniques, and hence the operational experiences in standard treatment practices provide useful guidelines. Composting also is not source reduction, but it is a form of recycling.

SIZE REDUCTION

As received, most solid waste has a low bulk density and is composed of a wide variety of objects in all sizes and shapes. This is especially the case for MSW. Solid waste shredding machines are not capable of destroying waste matter, but only of converting it into a form more easily and economically handled for processing. Hammer mills in one adaptation or another are the most commonly used size reduction machine.

The machines are variously called shredders, crushers, pulverizers, mills, and hoggers. Shredder is the most frequently used term. At one time, both capacity and durability posed important limitations to the application of waste shredders on a large scale. This is no longer true. Today, shredders are in service which
can nuggetize two complete automobiles per minute. Capacities of the largest waste shredders exceed 100 tons/hr.

The most common shredder design consists of a welded steel frame protected on the interior with abrasion-resistant steel alloy liners. Within the frame, there is a power-driven rotor with rows of pivoted manganese steel hammers.

For handling oversize bulky waste and other hard refuse, hammers are free to pivot back under impact to give relief from overload or shock. A series of sizing grates are positioned below the rotor. The violent hammer action reduces the material to a size that will pass through openings in the grates. Maximum product size can be controlled by installing grates with large or small openings. Figure 1 illustrates key features found in a hammer mill.

![Hammer mill features](image)

Figure 1. Hammer mill features.

Characteristics of shredded waste differ somewhat from those of other materials which are processed in shredders and hammer mills. With many materials, it is possible to arrive at a screen analysis or size degradation which tells the size of
the particles produced, as well as the relative quantity of the various size particles. However, because of the variety of materials contained in solid waste and seasonal variations which can be expected, a quantitative analysis of size degradation is almost impossible.

Shredder size should be selected to allow for anticipated surges in the rate of material feed. In addition to processing the hourly tonnage of materials, a refuse shredder must be sized to accommodate the largest pieces anticipated. Size reduction machines consume power in proportion to the feed rate and to the degree to which material is reduced. Little or no shock loading will occur when processing small pieces of wood, paper, corrugated board, bottles, plastic, and assorted organic matter. However, where a shredder must handle oversize bulky waste such as rubber tires, mattresses, refrigerators, stoves, tree limbs, furniture, packing crates, and demolition lumber, the power source and the drive train must be designed to withstand shock loading. For most solid waste applications, a motor is selected to provide between 12 and 20 horsepower per ton of refuse per hour. Shredder output is characterized by the maximum particle size though much of the product will be far smaller. Arbitrarily specifying a small final product will mean increasing shredder size, cost, power requirements, and cost of maintenance over the operating life of the installation. Shredder output can range from as large as 10 in. for landfilling to as small as 1 in. for composting.

To reduce the cost per ton of MSW handling, many communities have installed transfer stations. At the transfer station, small payload collection trucks are unloaded and quickly returned to neighborhood route service. Refuse is shredded to reduce bulk and improve handling characteristics. Compaction immediately after shredding can reduce the waste to one-third of its original volume.

Shredders can help a waste incineration plant operate more effectively. Even when physical size of the waste is not the limiting factor, firing theory indicates that more efficient combustion will occur when solid waste material is first shredded.

Modern high-capacity composting operations would not be possible without the use of shredding machines. In these plants, shredders reduce waste to a size which can be quickly decomposed by bacterial action. Composting plants operate best with a relatively fine particle size.

The process is speeded if fibrous material is also opened. To produce the required fineness at high material flow rates, composting operations usually employ two shredders in series. Following bacterial decomposition, a third
shredder may be used to thoroughly mix the compost and to break up any agglomerates not destroyed in the digester tank. Output size from the secondary refuse shredder operation will usually be on the order of 1 in.

Shredding is also used in conjunction with sanitary landfilling operations. When deposited in a landfill, waste shredded to a maximum size of 6 to 10 in. will not support combustion, will not support vermin, will not produce odor, and will not provide a breeding ground for insects.

Reduced volume of the shredded waste leads to prolonged life of the landfill site. Materials such as rubber tires and demolition lumber which could not previously be effectively compacted into a landfill present no problem after shredding. The effective life of the landfill site is prolonged from two to three times that normally expected, and the expense for covering the site daily with topsoil is eliminated.

CONCENTRATING METHODS

Concentrating methods are most often applied in industrial and wastewater treatment applications, where sludges are recovered during various treatment stages. By reducing the volume of sludge to be disposed of, savings for transport and ultimate disposal can be achieved. In wastewater treatment applications these methods are more commonly referred to as dewatering.

The objective of dewatering (also called sludge thickening) is to concentrate the sludge, and make it as dry as economically possible for post processing and disposal purposes. There are both mechanical and thermal techniques for achieving this. This section only describes mechanical methods.

Among the mechanical processes used to dewater sludge are belt filter presses and drum filters (vacuum technologies), pressure filter presses, and centrifugation.

VACUUM FILTRATION

The vacuum filter for dewatering sludge is a drum over which is laid the filtering medium consisting of a cloth of cotton, wool, nylon, Dynel, fiberglass, or plastic; a stainless-steel mesh, or a double layer of stainless-steel coil springs. The drum with horizontal axis is set in a tank with about one-quarter of the drum submerged in conditioned sludge. Valves and piping are so arranged that, as a portion of the drum rotates slowly in the sludge, a vacuum is applied on the inner side of the filter medium, drawing out water from the sludge and holding the
sludge against it. The application of the vacuum is continued as the drum rotates out of the sludge and into the atmosphere. This pulls water away from the sludge, leaving a moist mat or cake on the outer surface. This mat is scraped, blown, or lifted away from the drum just before it enters the sludge tank again. The common measure of performance of vacuum filters is the rate in pounds per hour of dry solids filtered per square foot of filter surface. For various sludge this rate may vary from a low of 2.5 for activated sludge to a high of 6 to 11 for the best digested primary sludge. The moisture content in the sludge cake also varies with the type of sludge, from 80 to 84% for raw activated sludge to 60 to 68% for well-digested primary sludge. While operating costs, including conditioning of sludge for vacuum filtration, are usually higher than with sludge beds, filtration has the advantage of requiring much less area, is independent of seasons and weather conditions, and can eliminate the necessity for digestion, since raw sludge can be dewatered sufficiently to be incinerated.

Proper care may prolong of the life of the material used as the filter. Such care includes washing of the filter material with the spray jets after every period of use, removal of grease and fats with warm soap solution if clogged, treatment with diluted hydrochloric acid for removal of lime encrustations, and maintenance of the scraper blade in careful adjustment to the filter drum to prevent tearing of the filter material.

CHEMICAL USE

Diluted ferric chloride solutions (10 to 20%) usually give better results in the conditioning of the sludge. A high-calcium lime is preferable or sludge filtration work. One should avoid excessive use of chemicals. The quantities of chemicals used for conditioning can be frequently reduced by careful control of the mixing and flocculation equipment. The maintenance of a uniform vacuum is necessary for satisfactory operation. Loss or fluctuations in vacuum usually indicate a break in the filter material, poorly conditioned sludge, or uneven distribution of the sludge solids in the filter pan.
ROTARY DRUM PRECOAT FILTER

This machine is used to polish solutions having traces of contaminating insolubles, so it is not a dewatering machine per se, but its use is often integrated into the process. To polish the solution, the drum deck is precoated with a medium of a known permeability and particle size that retains the fines and produces a clear filtrate. The following materials are used to form the precoat bed: diatomaceous earth (or diatomite) consisting of siliceous skeletal remains of tiny aquatic unicellular plants; perlite consisting of glassy crushed and heat-expanded rock of volcanic origin; and cellulose consisting of fibrous lightweight and ashless paperlike medium. Special ground wood has also become popular in recent years because it is combustible and reduces the high cost of disposal. There are manufacturers nowadays that grind, wash, and classify special timber to permeabilities, which can suit a wide range of applications. These materials when related to precoating are wrongly called filter aids since they do not aid filtration but serve as a filter medium in an analogy to the filter cloth on a conventional drum filter.

The precoat filter is similar in appearance to a conventional drum filter but its construction is very different. The scraper blade on conventional drum filters is stationary and serves mainly to deflect the cake while it is back-blown at the point of discharge. The scraper on a precoat filter, which is also called the doctor blade, moves slowly toward the drum and shaves off the blinding layer of the contaminants together with a thin layer of the precoating material. This movement continuously exposes a fresh layer of the precoat surface so that when the drum submerges into the tank it is ready to polish the solution. The blade movement mechanism is equipped with a precision drive having an adjustable advance rate of 1 to 10 mm/hr. The selected rate is determined by the penetration of fines into the precoat bed, which in turn depends on the permeability of the filter aid. Once the entire precoat is consumed the blade retracts at a fast rate so that the filter is ready for a new precoating cycle. The cake discharges on conventional drum filters by blow-back; hence a section of the main valve's bridge setting is allocated for this purpose. On precoat filters the entire drum deck is subjected to vacuum; therefore, there are two design options:

- A conventional valve that is piped, including its blow-back section, to be open to vacuum during polishing. When the precoat is consumed its blow-back section is turned on to remove the remaining precoat heel over the doctor blade.
- A valveless configuration in which there is no bridge setting and the sealing
between the rotating drum and the stationary outlet is by circumferential O-rings rather than by a face seal used on conventional valves.

The flow scheme for a conventional precoat filter station typically looks like that shown in Figure 2. The doctor blade discharge configuration for this machine is illustrated in Figure 3.

![Figure 2. Precoat drum filter flow scheme for polishing operations.](image)

**PRESSURE FILTRATION**

Pressure filtration is a process similar to vacuum filtration where sludge solids are separated from the liquid. Leaf filters probably are the most common type of unit. As in vacuum filtration, a porous medium is used in leaf filters to separate solids from the liquid. The solids are captured in the media pores; they build up on the media surface; and they reinforce the medium in its solid-liquid
separation action. Sludge pumps provide the energy to force the water through the medium. Lime, aluminum chloride, aluminum chlorohydrate, and ferric salts have been commonly used to condition sludge prior to pressing.

Figure 3. Doctor blade discharge for precoat filter.

The successful use of ash precoating is also prevalent. Minimum chemical costs are supposed to be the major advantage of press filters over vacuum filters. Leaf filters represent an attempt to dewater sludge in a small space quickly. But, when compared to other dewatering methods, they have major disadvantages, including (1) batch operation and (2) high operation and maintenance costs. Some other types of pressure filters include hydraulic and screw presses, which while effective in dewatering sludges, have the major disadvantage of usually requiring a thickened sludge feed. Sludge cakes containing as high as 75% solids using pressure filtration have been reported.
CENTRIFUGE DEWATERING

Centrifuges are machines that separate solids from the liquid through sedimentation and centrifugal force. In a typical unit sludge is fed through a stationary feed tube along the centerline of the bowl through a hub of the screw conveyor. The screw conveyor is mounted inside the rotating conical bowl. It rotates at a slightly lower speed than the bowl. Sludge leaves the end of the feed tube, is accelerated, passes through the ports in the conveyor shaft, and is distributed to the periphery of the bowl. Solids settle through the liquid pool, are compacted by centrifugal force against the walls of the bowl, and are conveyed by the screw conveyor to the drying or beach area of the bowl. The beach area is an inclined section of the bowl where further dewatering occurs before the solids are discharged. Separated liquid is discharged continuously over adjustable weirs at the opposite end of the bowl. The important process variables are: (1) feed rate, (2) sludge solids characteristics, (3) feed consistency, (4) temperature, and (5) chemical additives. Machine variables are: (1) bowl design, (2) bowl speed, (3) pool volume, and (4) conveyor speed. Two factors usually determine the success or failure of centrifugation: cake dryness and solids recovery. The effect of the various parameters on these two factors are listed below:

To increase cake dryness:
1. Increase bowl speed
2. Decrease pool volume
3. Decrease conveyor speed
4. Increase feed rate
5. Decrease feed consistency
6. Increase temperature
7. Do not use flocculants

To increase solids recovery:
1. Increase bowl speed
2. Increase pool volume
3. Decrease conveyor speed
4. Decrease feed rate
5. Increase temperature
6. Use flocculants
7. Increase feed consistency

Centrifugation has some inherent advantages over vacuum filtration and other processes used to dewater sludge. It is simple, compact, totally enclosed, flexible, can be used without chemical aids, and the costs are moderate. Industry particularly has accepted centrifuges in part because of their low capital cost, simplicity of operation, and effectiveness with difficult-to-dewater sludges. The most effective centrifuges to dewater waste sludges are horizontal or cylindrical conical, solid-bowl machines. Basket centrifuges dewater sludges effectively but
liquid clarification is poor. Disk-type machines do a good job of clarification but their dewatering capabilities leave much to be desired. Centrifuges are being installed in more and more wastewater treatment plants for the following reasons: (1) the capital cost is low in comparison with other mechanical equipment, (2) the operating and maintenance costs are moderate, (3) the unit is totally enclosed so odors are minimized, (4) the unit is simple and will fit in a small space, (5) chemical conditioning of the sludge is often not required, (6) the unit is flexible in that it can handle a wide variety of solids and function as a thickening as well as a dewatering device, (7) little supervision is required, and (8) the centrifuge can dewater some industrial sludges that cannot be handled by vacuum filters.

The poor quality of the centrate is a major problem with centrifuges. The fine solids in centrate recycled to the head of the treatment plant sometimes resist settling and as a result, their concentrations in the treatment system gradually build up. The centrate from raw sludge dewatering can also cause odor problems when recycled. Flocculants can be used to increase solids captures, often to any degree desired, as well as to materially increase the capacity (solids loading) of the centrifuges. However, the use of chemicals nullifies the major advantage claimed for centrifuges - moderate operating costs. As noted, three basic types of centrifuges are disk-nozzle, basket, and solid bowl. The latter two types have been used extensively for both dewatering and thickening. The disk-nozzle centrifuge is seldom used for dewatering sludge, but is used more for sludge thickening in the industrial sector. Because the solid-bowl design has undergone major improvements throughout the history of its use, this method is used more than any other to dewater sludge. Because of recent improvements in solid-bowl centrifuge design, solid concentrations can reach 35%.

![Continuous solid-bowl centrifuge](image.png)

Figure 4. Continuous solid-bowl centrifuge.
The solid-bowl conveyor centrifuge operates with a continuous feed and discharge rates. It has a solid-walled imperforated bowl, with a horizontal axis of rotation. These centrifuges are enclosed, so they have a limited odor potential compared with other dewatering methods. The laydown area, access area, and centrifuge required space for a large machine (200 m to 700 gpm of sludge feed) is approximately 400 ft². Compared to other mechanical dewatering machines, this space is significantly smaller. An example of a continuous horizontal solid-bowl centrifuge is illustrated in Figure 4. It consists of a cylindrical rotor with a truncated cone-shaped end and an internal screw conveyor rotating together. The screw conveyor often rotates at a rate of 1 or 2 rpm below the rotor’s rate of rotation. The suspension enters the bowl axially through the feed tube to a feed accelerated zone, then passes through a feed port in the conveyor hub into the pond. The suspension is subjected to centrifugal force and thrown against the bowl wall where the solids are separated. The clarified suspension moves toward the broad part of the bowl to be discharged through a port. The solid particles being scraped by the screw conveyor are carried in the opposite direction (to the small end of the bowl) across discharge ports through which they are ejected continuously by centrifugal force. As in any sedimentation centrifuge, the separation takes place in two stages: settling (Figure 4, in the right part of the bowl), and thickening or pressing out of the sediment (left-hand side of the bowl).

Because the radius of the solid discharge port is usually less than the radius of the liquid overflow at the broader end of the bowl, part of the settled solids is submerged in the pond. The remainder, closer to the center, is inside the free liquid interface, where they can drain before being discharged. The total length of the settling and pressing-out zones depends on the dimensions of the rotor. Their relative length can be varied by changing the pond level through suitable adjustment of the liquid discharge radius. When the pond depth is lowered, the length of the pressing-out zone increases with some sacrifice in the clarification effectiveness. The critical point in the transport of solids to the bowl wall is their transition across the free liquid interface, where the buoyancy effect of the continuous phase is lost. At this point, soft amorphous solids tend to flow back into the pond instead of discharging. This tendency can be overcome by raising the pond level so that its radius is equal to, or less than, that of the solids discharge port. In reality, there are no dry settled solids. The solids form a dam, which prevents the liquid from overflowing. The transfer of solids becomes possible because of the difference between the rotational speed of the screw conveyor and that of the bowl shell. The flights of the screw move through the settled solids and cause the solids to advance. To achieve this motion, it is necessary to have a high circumferential coefficient of friction on the solid
particles with respect to the bowl shell and a low coefficient axially with respect to the bowl shell and across the conveyor flights. These criteria may be achieved by constructing the shell with conical grooves or ribs and by polishing the conveyor flights. The conveyor or differential speed is normally in the range of 0.8 to 5% of the bowl’s rotational speed.

The required differential is achieved by a two-stage planetary gear box. The gear box housing carrying two ring gears is fixed to, and rotates with, the bowl shell. The first-stage pinion is located on a shaft that projects outward from the housing. This arrangement provides a signal that is proportional to the torque imposed by the conveyor. If the shaft is held rotationally (for example, by a torque overload release device or a shear pin), the relative conveyor speed is equivalent to the bowl rotative speed divided by the gear-box ratio. Variable differential speeds can be obtained by driving the pinion shaft with an auxiliary power supply or by allowing it to slip forward against a controlled braking action. Both arrangements are employed when processing soft solids or when maximum retention times are needed on the pressing out zone. The solids-handling capacity of this type centrifuge is established by the diameter of the bowl, the conveyor’s pitch, and its differential speed. Feed ports should be located as far from the effluent discharge as possible to maximize the effective clarifying length. Note that the feed must be introduced into the pond to minimize disturbance and resuspension of the previously sedimented solids. As a general rule, the preferred feed location is near the intercept of the conical and cylindrical portions of the bowl shell. The angle of the sedimentation section with respect to the axis of rotation is typically in the range of 3° to 15°. A shallow angle provides a longer sedimentation area with a sacrifice in the effective length for clarification.

In some designs, a portion of the conveyor flights in the sedimentation area is shrouded (as with a cone) to prevent intermixing of the sedimented solids with the free supernatant liquid in the pond through which they normally would pass. In other designs, the clarified liquid is discharged from the front end via a centrifugal pump or an adjustable skimmer that sometimes is used to control the pond level in the bowl. Some displacement of the adhering virgin liquor can be accomplished by washing the solids retained on the settled layer, particularly if the solids have a high degree of permeability. Washing efficiency ranges up to 90% displacement of virgin liquor on coarse solids. Some configurations enable the settled layer to have two angles; comparatively steep in the wetted portion (10 to 15°) and shallow in the dry portion (3 to 5°). A wash is applied at the intersection of these angles, which, in effect, forms a constantly replenished zone of pure liquid through which the solids are conveyed. The longer section of a
dry shallow layer provides more time for drainage of the washed solids. In either washing system, the wash liquid that is not carried out with the solids fraction returns to the pond and eventually discharges along with the effluent virgin liquor.

**Disk-Bowl Centrifuges**

Disk-bowl centrifuges are used widely for separating emulsions, clarifying fine suspensions, and separating immiscible liquid mixtures. Although these machines are generally not applied to wastewater applications and are more usually found in food processing, they can find niche applications in water treatment. More sophisticated designs can separate immiscible liquid mixtures of different specific gravities while simultaneously removing solids. Figure 5 illustrates the physical separation of two liquid components within a stack of disks. The light liquid phase builds up in the inner section, and the heavy phase concentrates in the outer section.

![Figure 5. Separation is achieved by use of stack disks.](image-url)
The dividing line between the two is referred to as the *separating zone*. For the most efficient separation, this is located along the line of the rising channels, which are a series of holes in each disk, arranged so that the holes provide vertical channels through the entire disk set. These channels also provide access for the liquid mixture into the spaces between the disks. Centrifugal force causes the two liquids to separate, and the solids move outward to the sediment-holding space.

The position of the separating zone is controlled by adjusting the back pressure of the discharged liquids or by means of exchangeable ring dams. Figure 6 illustrates the main features of a disk-bowl centrifuge, which includes a seal ring (1); a bowl (2) with a bottom (13); a central tube (18), the lower part of which has a fixture (16) for disks; a stack of truncated cone disks (17), frequently flanged at the inside and outer diameters to add strength and rigidity; collectors (3 and 4) for the products of separation; and a feed tank (5) with a tube (6).

![Figure 6. Details of disk-bowl centrifuge.](image-url)
The bowl is mounted to the tube (14) with a guide in the form of a horizontal pin. This arrangement allows the bowl to rotate along with the shaft. The suspension is supplied from the feed tank (5) through the fixed tube (6), to the central tube (18), which rotates together with the bowl and allows the liquid to descend to the bottom. In the lower part of the bowl, the suspension is subjected to centrifugal force and, thus, directed toward the periphery of the bowl. The distance between adjacent disks is controlled by spacers that usually are radial bars welded to the upper surface of each disk. The suspension may enter the stack at its outside diameter or through a series of vertical channels cut through the disks, as described earlier. The suspension is lifted up through vertical channels formed by the holes in the disks and distributed simultaneously under the action of centrifugal force into the spacings between the disks. These spacings are of tight tolerances and can range from 0.3 to 3 mm.

Because of its larger diameter, the disk bowl operates at a lower rotational speed than its tubular counterpart. Its effectiveness depends on the shorter path of particle settling. The maximum distance a particle must travel is the thickness of the spacer divided by the cosine of the angle between the disk wall and the axis of rotation. Spacing between disks must be wide enough to accommodate the liquid flow without promoting turbulence and large enough to allow sedimented solids to slide outward to the grit-holding space without interfering with the flow of liquid in the opposite direction.

The disk angle of inclination (usually in the range of 35° to 50°) generally is small to permit the solid particles to slide along the disks and be directed to the solids-holding volume located outside of the stack. Dispersed particles transfer from one layer to the other; therefore, the concentration in the layers and their thickness are variables. The light component from the spacing near central tube (18) falls under the disk; then it flows through the annular gap between tube (18) and the cylindrical end of the dividing disk, where it is ejected through the port (7) into the circular collector (4) and farther via the funnel (9) on being discharged to the receiver. The heavier product is ejected to the bowl wall and raised upward. It enters the space between the outside surface of the dividing disk and the cone cover (2), then passes through the port (8) and is discharged into the collector (3). From there, the product is transferred to the funnel (10).
THICKENERS

Thickening is practiced in order to remove as much water as possible before final dewatering of the sludge. It is usually accomplished by floating the solids to the top of the liquid (floatation) or by allowing the solids to settle to the bottom (gravity thickening). Other methods of thickening include centrifuging, gravity belts, and rotary drum thickening. These processes offer a low-cost means of reducing the volumetric loading of sludge to subsequent steps.

In the flotation thickening process air is injected into the sludge under pressure. The resulting air bubbles attach themselves to sludge solids particles and float them to the surface of an open tank. The sludge forms a layer at the top of the tank which is removed by a skimming mechanism. This process increases the solids concentration of activated sludge from 0.5 to 1% to 3 to 6%.

Gravity thickening has been widely used on primary sludge for many years because of its simplicity and inexpensiveness. In gravity thickening, sludge is concentrated by the gravity-induced settling and compaction of sludge solids. It is essentially a sedimentation process. Sludge flows into a tank that is similar to the circular clarifiers used in primary and secondary sedimentation. The solids in the sludge settle to the bottom where a scraping mechanism removes them to a hopper. The type of sludge being thickened has a major effect on performance. The best results can be achieved with primary sludge. Purely primary sludge can be thickened from 1 to 3% up to 10% solids. As the proportion of activated (secondary) sludge increases, the thickness of settled solids decreases.

There are various designs for sludge thickeners and any standard textbook on wastewater treatment technology will provide the reader with further details. There are a variety of technologies from which to select for sludge dewatering operations. Each has its own set of advantages, disadvantages, and limitations in operating ranges.

Selection greatly depends on the volumes and nature of the sludge. Table 1 provides a relative comparison between the principal mechanical dewatering techniques.
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<tr>
<th>Technology or method</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td><strong>Gravity</strong></td>
<td>Simple</td>
<td>Potential for obnoxious and harmful odors</td>
</tr>
<tr>
<td></td>
<td>Low operating and maintenance costs</td>
<td>Thickened sludge concentration limited for WAS</td>
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<td></td>
<td>Low operator attention and moderate training requirements</td>
<td>High space requirements for WAS</td>
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<td></td>
<td>Minimal power consumption</td>
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<tr>
<td><strong>Dissolved air flotation</strong></td>
<td>Effective for WAS</td>
<td>Relatively high power consumption</td>
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<td></td>
<td>Can work without conditioning chemicals</td>
<td>Thickening solids concentration limited</td>
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<td></td>
<td>Relatively simple equipment components</td>
<td>Potential for obnoxious and harmful odors</td>
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<tr>
<td><strong>Centrifugation</strong></td>
<td>Low space requirements</td>
<td>Best suited for continuous operations</td>
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<td></td>
<td>Effective for WAS</td>
<td>Sophisticated maintenance requirements</td>
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<td></td>
<td>Minimum housekeeping and odor problems</td>
<td>Relatively high power consumption</td>
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<td></td>
<td>Highly thickened concentrations available</td>
<td>Relatively high capital cost</td>
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<tr>
<td><strong>Rotating drum filter</strong></td>
<td>Low space requirements</td>
<td>Can be polymer dependent</td>
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<td></td>
<td>Low capital cost</td>
<td>Sensitive to polymer type</td>
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<td></td>
<td>Relatively low power consumption</td>
<td>Housekeeping requirements high</td>
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<td></td>
<td>High solids capture achievable</td>
<td>Potential for obnoxious and harmful odors</td>
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<td>Moderate operator attention and training requirements</td>
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### TECHNOLOGY OR METHOD

<table>
<thead>
<tr>
<th>Technology or method</th>
<th>Advantages</th>
<th>Disadvantages</th>
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| Gravity belt thickener | Low space requirements  
Relatively low power consumption  
Relatively low capital cost  
Can achieve high thickened concentrations and solids capture with minimum power | Housekeeping requirements high  
Can be polymer dependent  
Moderate operator attention and training requirements  
Potential for obnoxious and harmful odors |

### INCINERATION OF MUNICIPAL SLUDGE

Incineration of municipal wastewater treatment sludge is widely practiced in many parts of the world. Its application is the reduction in the volume and weight of end product to be disposed of. There is a minimum size of sewage treatment plant below which incineration is not economical. There must be enough sludge to necessitate reasonable use of costly equipment. One of the difficulties in operating an incinerator is variations in tonnage and moisture of sludge handled. There are two major incinerator technologies used in this process. They are (1) the multiple hearth incinerator and (2) the fluidized-bed incinerator. An incinerator is usually part of a sludge treatment system which includes sludge thickening, macerations, dewatering (such as vacuum filter, centrifuge, or filter press), an incinerator feed system, air pollution control devices, ash handling facilities, and the related automatic controls. The operation of the incinerator cannot be isolated from these other system components. Of particular importance is the operation of the thickening and dewatering processes because the moisture content of the sludge is the primary variable affecting the incinerator fuel consumption.

Incineration may be thought of as the complete destruction of materials by heat to their inert constituents. This material that is being destroyed is the waste product (i.e., the sludge). Sewer sludge as sludge cake normally contains from 55 to 85% moisture. It cannot burn until the moisture content has been reduced to no more than 30%.

The purpose of incineration is to reduce the sludge cake to its minimum volume, as sterile ash. There are three objectives incineration must accomplish:
• Dry the sludge cake
• Destroy the volatile content by burning
• Produce a sterile residue or ash

There are four basic types of incinerators used in wastewater treatment plants. They are the multiple hearth incinerator, the fluid bed incinerator, the electric furnace, and the cyclonic furnace. Each system has its own distinct method of incineration and while one may be more cost efficient, another may have more of an environmental impact.

Sewage sludge ash is the by-product produced during the combustion of dewatered sewage sludge in an incinerator. Sewage sludge ash is primarily a silty material with some sand-size particles. The specific size range and properties of the sludge ash depend to a great extent on the type of incineration system and the chemical additives introduced in the wastewater treatment process. Two major incineration systems, multiple hearth and fluidized bed, are employed in the United States, with approximately 80% of the incinerators being multiple hearth designs. The multiple-hearth incinerator is a circular steel furnace that contains a number of solid refractory hearths and a central rotating shaft. Rabble arms that are designed to slowly rake the sludge on the hearth are attached to the rotating shaft. Dewatered sludge (approximately 20% solids) enters at the top and proceeds downward through the furnace from hearth to hearth, pushed along by the rabble arms. Cooling air is blown through the central column and hollow rabble arms to prevent overheating. The spent cooling air with its elevated temperature is usually recirculated and used as combustion air to save energy. Flue gases are typically routed to a wet scrubber for air pollution control. The particulates collected in the wet scrubber are usually diverted back into the sewage plant.

Fluidized bed incinerators consist of a vertical cylindrical vessel with a grid in the lower sections to support a bed of sand. Dewatered sludge is injected into the lower section of the vessel above the sand bed and combustion air flows upward and fluidizes the mixture of hot sand and sludge. Supplemental fuel can be supplied by burning above and below the grid if the heating value of the sludge and its moisture content are insufficient to support combustion.

Figure 7 illustrates a simplified flow diagram of a sludge incinerator. The complete system includes sludge pretreatment operations such as sludge thickening (sedimentation) and sludge dewatering (vacuum filter, centrifuge, or filter press), followed by incineration, air pollution control, and ash handling. Sludge dewatering may involve the addition of ferrous chloride, lime, or organic polymers to enhance the dewatering process. Auxiliary fuel is normally needed to
maintain the combustion process. The quantity of auxiliary fuel required depends on the heating value of the sludge solids and, primarily, on the moisture content of the incoming feed sludge. Operating temperatures can vary, depending on the type of furnace, but can be expected to range from approximately 650°C (1200°F) to 980°C (1800°F) in the incinerator combustion zone. High operating temperatures above 900°C (1650°F) can result in partial fusion of ash particles and the formation of clinkers, which end up in the ash stream. Lime may also be added to reduce the slagging of sludge during incineration. Incineration of sewage sludge (dewatered to approximately 20% solids) reduces the weight of feed sludge requiring disposal by approximately 85%. There are approximately 170 municipal sewage treatment plant incinerators in the United States, processing approximately 20% of the country’s sludge, and producing between 0.45 million and 0.9 million metric tons (0.5 and 1.0 million tons) of sludge ash on an annual basis.

Figure 7. Sewage sludge incineration process.
INCINERATOR ASH PROPERTIES

Table 2 provides literature reported values of physical property characterization data for sludge ash. Sludge ash is a silty-sandy material. A relatively large fraction of the particles (up to 90% in some ashes) are less than 0.075 mm (No. 200 sieve) in size. Sludge ash has a relatively low organic and moisture content. Permeability and bulk specific gravity properties are not unlike those of a natural inorganic silt. Sludge ash is a nonplastic material.

Sludge ash consists primarily of silica, iron, and calcium. The composition of the ash can vary significantly and depends in great part on the additives introduced in the sludge conditioning operation. There are no specific data available relative to the pozzolanic or cementitious properties of sludge ash, but sludge ash is not expected to exhibit any measurable pozzolanic or cementitious activity. Table 3 lists the range of major elemental concentrations present in sludge ash.

Trace metal concentrations (e.g., lead, cadmium, zinc, copper) found in sludge ash are typically higher than concentrations found in natural fillers or aggregate. This has resulted in some reluctance to use this material; however, recent investigations (leaching tests) suggest that these trace metal concentrations are not excessive and do not pose any measurable leaching problem.

Table 2. Typical Physical Properties of Sewage Sludge Ash

<table>
<thead>
<tr>
<th>Property</th>
<th>Wegman&lt;sup&gt;(10)&lt;/sup&gt;</th>
<th>Khanbiluardi&lt;sup&gt;(11)&lt;/sup&gt;</th>
<th>Waste Commission&lt;sup&gt;(6)&lt;/sup&gt;</th>
<th>Gray&lt;sup&gt;(15)&lt;/sup&gt;</th>
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</thead>
<tbody>
<tr>
<td>Gradation (% passing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.76 mm (No. 4 sieve)</td>
<td>99</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2.38 mm (No. 8 sieve)</td>
<td>99</td>
<td>98</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2.00 mm (No. 10 sieve)</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>0.85 mm (No. 20 sieve)</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>0.42 mm (No. 40 sieve)</td>
<td>99</td>
<td>73</td>
<td>98</td>
<td>-</td>
</tr>
<tr>
<td>0.21 mm (No. 80 sieve)</td>
<td>-</td>
<td>-</td>
<td>83</td>
<td>-</td>
</tr>
<tr>
<td>0.149 mm (No. 100 sieve)</td>
<td>85</td>
<td>53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.074 mm (No. 200 sieve)</td>
<td>66</td>
<td>38</td>
<td>56</td>
<td>47-93</td>
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</table>
VOLUME REDUCTION TECHNOLOGIES

<table>
<thead>
<tr>
<th>Property</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradation (% passing)</td>
<td>Wegman(^{(10)})  Khanbiluardi(^{(11)})</td>
</tr>
<tr>
<td>- (0.0902 mm)</td>
<td>10-13</td>
</tr>
<tr>
<td>0.02 mm</td>
<td>-</td>
</tr>
<tr>
<td>0.005 mm</td>
<td>-</td>
</tr>
<tr>
<td>&gt;0.001 mm</td>
<td>-</td>
</tr>
<tr>
<td>Loss on Ignition (%)</td>
<td>1.4(^{(10)})</td>
</tr>
<tr>
<td>Moisture Content (% by Total Weight)</td>
<td>0.28(^{(11)})</td>
</tr>
<tr>
<td>Absorption (%)</td>
<td>1.6(^{(6)})</td>
</tr>
<tr>
<td>Specific Gravity (ASTM D2434 - cm/sec)</td>
<td>2.44 - 2.96(^{(15)})</td>
</tr>
<tr>
<td>Bulk Specific Gravity</td>
<td>1.82(^{(11)})</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>Nonplastic(^{(10)})</td>
</tr>
<tr>
<td>Permeability</td>
<td>4 x 10^-4</td>
</tr>
<tr>
<td>(ASTM D2434 - cm/sec)</td>
<td>1 x 10^-4 - 4 x 10^-4(^{(6)})</td>
</tr>
</tbody>
</table>

Table 3. Typical Range of Elemental Concentrations in Sewage Sludge Ash

<table>
<thead>
<tr>
<th>Element</th>
<th>Oxide</th>
<th>Concentration %</th>
<th>Concentration %</th>
<th>Concentration %</th>
<th>Concentration %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Reported as elemental concentration(^{(2)})</td>
<td>Reported as elemental concentration(^{(6)})</td>
<td>Reported as oxides(^{(10,16)})</td>
<td>Reported as oxides(^{(15)})</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>(SiO(_2))</td>
<td>5.6-25.7</td>
<td>20</td>
<td>27.0</td>
<td>14.4-57.7</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>(CaO)</td>
<td>1.4-42.9</td>
<td>8</td>
<td>21.0</td>
<td>8.9-36.9</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>(Fe(_2)O(_3))</td>
<td>1.0-16.4</td>
<td>4</td>
<td>8.2</td>
<td>2.6-24.4</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>(Al(_2)O(_3))</td>
<td>1.1-8.5</td>
<td>7</td>
<td>14.4</td>
<td>4.6-22.1</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>(MgO)</td>
<td>0.6-1.9</td>
<td>2</td>
<td>3.2</td>
<td>0.8-2.2</td>
</tr>
<tr>
<td>Sodium</td>
<td>(Na(_2)O)</td>
<td>0.1-0.8</td>
<td>0.3</td>
<td>0.5</td>
<td>0.1-0.7</td>
</tr>
<tr>
<td>Element</td>
<td>Oxide</td>
<td>Reported as elemental concentration(^{(2)})</td>
<td>Reported as elemental concentration(^{(6)})</td>
<td>Reported as oxides(^{(10,16)})</td>
<td>Reported as oxides(^{(15)})</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>---------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>(K(_2)O)</td>
<td>0.3-1.6</td>
<td>0.5</td>
<td>0.6</td>
<td>0.07-0.7</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>(P(_2)O(_5))</td>
<td>1.2-4.4</td>
<td>6</td>
<td>20.2</td>
<td>3.9-15.4</td>
</tr>
<tr>
<td>Sulfur (S)</td>
<td>(SO(_3))</td>
<td>0.3-1.2</td>
<td>-</td>
<td>0.9</td>
<td>0.01-3.4</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>-</td>
<td>0.6-2.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

References at the end of this chapter may be consulted for the sources of data in Tables 2 and 3 as well as additional information.

**MULTIPLE HEARTH INCINERATORS**

This incinerator is the most prevalent incinerator technology for the disposal of sewage sludge in the United States because of its low ash discharge. Sludge cake enters the furnace at the top. The interior of the furnace is composed of a series of circular refractory hearths, which are stacked one on top of the other. There are typically five to nine hearths in a furnace. A vertical shaft, positioned in the center of the furnace has rabble arms with teeth attached to them in order to move the sludge through the mechanism. Each arm is above a layer of hearth. Teeth on each hearth agitate the sludge, exposing new surfaces of the sludge to the gas flow within the furnace. As sludge falls from one hearth to another, it again has new surfaces exposed to the hot gas. At the top of the incinerator there is an exit for flue gas, an end product of sludge incineration. At the bottom of the furnace there is an exit for the ashes. Figure 8 illustrates the key design features.

Partially dewatered sludge is fed onto the perimeter of the top hearth. The rabble arms move the sludge through the incinerator by raking the sludge toward the center shaft where it drops through holes located at the center of the hearth. In the next hearth the sludge is raked in the opposite direction.
This process is repeated in all of the subsequent hearths. The effect of the rabble motion is to break up solid material to allow better surface contact with heat and oxygen. A sludge depth of about 1 in. is maintained in each hearth at the design sludge flow rate. Scum may also be fed to one or more hearths of the incinerator. Scum is the material that floats on wastewater. It is generally composed of vegetable and mineral oils, grease, hair, waxes, fats, and other materials that will float. Scum may be removed from many treatment units.
including preaeration tanks, skimming tanks, and sedimentation tanks. Quantities of scum are generally small compared to those of other wastewater solids. Ambient air is first ducted through the central shaft and its associated rabble arms. A portion, or all, of this air is then taken from the top of the shaft and recirculated into the lowermost hearth as preheated combustion air. Shaft cooling air which is not circulated back into the furnace is ducted into the stack downstream of the air pollution control devices. The combustion air flows upward through the drop holes in the hearths, countercurrent to the flow of the sludge, before being exhausted from the top hearth. Air enters the bottom to cool the ash. Provisions are usually made to inject ambient air directly into the middle hearths as well.

From the standpoint of the overall incineration process, multiple hearth furnaces can be divided into three zones. The upper hearths comprise the drying zone where most of the moisture in the sludge is evaporated. The temperature in the drying zone is typically between 425 and 760°C (800 and 1400°F). Sludge combustion occurs in the middle hearths (second zone) as the temperature is increased to about 925°C (1700°F). The combustion zone can be further subdivided into the upper-middle hearths where the volatile gases and solids are burned, and the lower-middle hearths where most of the fixed carbon is combusted. The third zone, made up of the lowermost hearth(s), is the cooling zone. In this zone the ash is cooled as its heat is transferred to the incoming combustion air.

Multiple hearth furnaces are sometimes operated with afterburners to further reduce odors and concentrations of unburned hydrocarbons. In afterburning, furnace exhaust gases are ducted to a chamber where they are mixed with supplemental fuel and air and completely combusted. Some incinerators have the flexibility to allow sludge to be fed to a lower hearth, thus allowing the upper hearth(s) to function essentially as an afterburner.

Under normal operating condition, 50 to 100% excess air must be added to an MHF in order to ensure complete combustion of the sludge. Besides enhancing contact between fuel and oxygen in the furnace, these relatively high rates of excess air are necessary to compensate for normal variations in both the organic characteristics of the sludge feed and the rate at which it enters the incinerator. When an inadequate amount of excess air is available, only partial oxidation of the carbon will occur, with a resultant increase in emissions of carbon monoxide, soot, and hydrocarbons. Too much excess air, on the other hand, can cause increased entrainment of particulate and unnecessarily high auxiliary fuel consumption.
FLUIDIZED-BED INCINERATOR

The basic configuration and features of the fluid bed incinerator have already been described. This technology has been around since the early 1960s. In this system, air is introduced at the fluidizing air inlet at pressures of 3.5 to 5 psig. The air passes through openings in the grid supporting the sand and creates fluidization of the sand bed. Sludge cake is introduced into the bed. The fluidizing air flow must be carefully controlled to prevent the sludge from floating on top of the bed.

Fluidization provides maximum contact of air with sludge surface for optimum burning. The drying process is practically instantaneous. Moisture flashes into steam upon entering the hot bed. Some advantages of this system are that the sand bed acts as a heat sink so that after shutdown there is minimal heat loss. With this heat containment, the system will allow startup after a weekend shutdown with need for only 1 or 2 hr of heating. The sand bed should be at least 1200°F when operating.

Fluidized bed technology was first developed by the petroleum industry to be used for catalyst regeneration. These are referred to as fluidized bed combustors (FBCs) and they consist of a vertically oriented outer shell constructed of steel and lined with refractory. Tuyeres (nozzles designed to deliver blasts of air) are located at the base of the furnace within a refractory-lined grid. A bed of sand, approximately 0.75 meters (2.5 feet) thick, rests upon the grid. Two general configurations can be distinguished on the basis of how the fluidizing air is injected into the furnace. In the "hot windbox" design the combustion air is first preheated by passing through a heat exchanger where heat is recovered from the hot flue gases. Alternatively, ambient air can be injected directly into the furnace from a cold windbox.

Partially dewatered sludge is fed into the lower portion of the furnace. Air injected through the tuyeres, at pressures of from 20 to 35 kilopascals (3 to 5 pounds per square inch gauge), simultaneously fluidizes the bed of hot sand and the incoming sludge. Temperatures of 750 to 925°C (1400 to 1700°F) are maintained in the bed. Residence times are typically 2 to 5 s. As the sludge burns, fine ash particles are carried out the top of the furnace. Some sand is also removed in the air stream; sand makeup requirements are on the order of 5% for every 300 hr of operation. Combustion of the sludge occurs in two zones. Within the bed itself (Zone 1), evaporation of the water and pyrolysis of the organic materials occur nearly simultaneously as the temperature of the sludge is rapidly raised. In the second zone (freeboard area), the remaining
free carbon and combustible gases are burned. The second zone functions essentially as an afterburner.

Fluidization achieves nearly ideal mixing between the sludge and the combustion air and the turbulence facilitates the transfer of heat from the hot sand to the sludge. The most noticeable impact of the better burning atmosphere provided by a fluidized bed incinerator is seen in the limited amount of excess air required for complete combustion of the sludge. Typically, FBCs can achieve complete combustion with 20 to 50% excess air, about half the excess air required by multiple hearth furnaces. As a consequence, FBC incinerators have generally lower fuel requirements compared to MHF incinerators. Fluidized-bed incinerators most often have venturi scrubbers or venturi/impingement tray scrubber combinations for emissions control.

ELECTRIC FURNACE

The electric furnace is basically a conveyor belt system passing through a long rectangular refractory lined chamber. Heat is provided by electric infrared heating elements within the furnace. Cooling air prevents local hot spots in the immediate vicinity of the heaters and is used as secondary combustion air within the furnace. The conveyer belt is made of continuous woven wire mesh chosen of steel alloy that will withstand the 1300 to 1500°F temperatures. The sludge on the belt is immediately leveled to 1 in. The belt speed is designed to provide burnout of the sludge without agitation. The first electric infrared furnace was installed in the 1970s, and their use is not common.

Electric infrared incinerators consist of a horizontally oriented, insulated furnace. A woven wire belt conveyor extends the length of the furnace and infrared heating elements are located in the roof above the conveyor belt. Combustion air is preheated by the flue gases and is injected into the discharge end of the furnace. Electric infrared incinerators consist of a number of prefabricated modules, which can be linked together to provide the necessary furnace length. A cross section of an electric furnace is shown in Figure 9. The dewatered sludge cake is conveyed into one end of the incinerator. An internal roller mechanism levels the sludge into a continuous layer approximately 1 in. thick across the width of the belt. The sludge is sequentially dried and then burned as it moves beneath the infrared heating. The ash is discharged into a hopper at the opposite end of the furnace. Preheated combustion air enters the furnace above the ash hopper and undergoes further heating by the exiting ash. The air flow direction is countercurrent to the sludge flow along the conveyor.
Exhaust gases leave the furnace at the end of the feed. The excess air can vary from 20 to 70%. These systems offer the advantage of lower capital cost for smaller systems. High electricity costs in some areas make this technology too costly.

Figure 9. Electric arc furnace.

CYCLONE FURNACE

The cyclonic furnace is a single hearth unit where the hearth moves and the rabble teeth are stationary. Sludge is moved toward the center of the hearth where it is discharged as ash. The furnace is a refractory lined cylindrical shell with a domed top. The air, heated with the immediate introduction of supplemental fuel, creates a violent swirling pattern which provides good mixing of air and sludge feed. The air, which later turns into flue gas, swirls up vertically in cyclonic flow through the discharge flue in the center of the domed
roof. One advantage of these furnaces is that they are relatively small and can be placed in operation, at operating temperature, within an hour.

As ash falls into a wet sump, turbulence is created by the entrance of water. This turbulence is necessary so that the ash doesn't collect and cake up. This water containing the ash is pumped into a holding pond or lagoon, with a residence time of at least 6 hours. During this time, 95% of the ash will have settled to the bottom and the overflow is taken back to the treatment plant. There has to be a minimum of two lagoons with one being used to hold the ash-water discharge and the other for drying. When dry, the ash is hauled to a landfill or used for concrete. Mixing one part of ash to four parts cement will produce a slow-setting concrete with no loss in strength.

**ENVIRONMENTAL IMPACT AND CONTROLS**

A serious environmental impact of incineration is on air quality. An incinerator's smoke discharge or flue gas should be colorless. Flue gas is an emission mainly made up of nitrogen, carbon dioxide, and oxygen. There are traces of chloride and sulfides in the gas and if these levels become too high, they could cause the possibility of corrosion. With respect to the color of the discharge again, if there is a significant amount of particulate matter in the emission, it will be detected by color. The stream can range from a black to white appearance and will have a pale yellow to dark brown trail. The discharge should also have no discernable odor and there should be no detectable noise due to incinerator operation at the property line. Unfortunately, colored emissions and odor problems do occur and treatment plants take the proper actions to correct it.

Air pollution controls are critical factors that add significant costs onto these technologies. Sewage sludge incinerators potentially emit significant quantities of pollutants. The major pollutants emitted are: (1) particulate matter, (2) metals, (3) carbon monoxide (CO), (4) nitrogen oxides (NOₓ), (5) sulfur dioxide (SO₂), and (6) unburned hydrocarbons. Partial combustion of sludge can result in emissions of intermediate products of incomplete combustion (PIC), including toxic organic compounds. Uncontrolled particulate emission rates vary widely depending on the type of incinerator, the volatiles and moisture content of the sludge, and the operating practices employed. Generally, uncontrolled particulate emissions are highest from fluidized-bed incinerators because suspension burning results in much of the ash being carried out of the incinerator with the flue gas.
Uncontrolled emissions from multiple hearth and fluidized-bed incinerators are extremely variable, however. Electric incinerators appear to have the lowest rates of uncontrolled particulate release of the three major furnace types, possibly because the sludge is not disturbed during firing. In general, higher airflow rates increase the opportunity for particulate matter to be entrained in the exhaust gases. Sludge with low volatile content or high moisture content may compound this situation by requiring more supplemental fuel to burn. As more fuel is consumed, the amount of air flowing through the incinerator is also increased. However, no direct correlation has been established between airflow and particulate emissions. Metal emissions are affected by metal content of the sludge, fuel bed temperature, and the level of particulate matter control. Since metals which are volatilized in the combustion zone condense in the exhaust gas stream, most metals (except mercury) are associated with fine particulates and are removed as the fine particulates are removed.

Carbon monoxide is formed when available oxygen is insufficient for complete combustion or when excess air levels are too high, resulting in lower combustion temperatures. Emissions of nitrogen and sulfur oxides are primarily the result of oxidation of nitrogen and sulfur in the sludge. Therefore, these emissions can vary greatly based on local and seasonal sewage characteristics. Emissions of volatile organic compounds (VOC) also vary greatly with incinerator type and operation. Incinerators with countercurrent airflow such as multiple hearth designs provide the greatest opportunity for unburned hydrocarbons to be emitted. In the MHF, hot air and wet sludge feed are contacted at the top of the furnace. Any compounds distilled from the solids are immediately vented from the furnace at temperatures too low to completely destroy them. Particulate emissions from sewage sludge incinerators have historically been controlled by wet scrubbers, since the associated sewage treatment plant provides both a convenient source and a good disposal option for the scrubber water.

The types of existing sewage sludge incinerator controls range from low pressure drop spray towers and wet cyclones to higher pressure drop venturi scrubbers and venturi/impingement tray scrubber combinations. Electrostatic precipitators and baghouses are employed primarily where sludge is co-fired with municipal solid waste. The most widely used control device applied to a multiple hearth incinerator is the impingement tray scrubber. Older units use the tray scrubber alone; combination venturi/impingement tray scrubbers are widely applied to newer multiple-hearth incinerators and to fluidized bed incinerators.
Most electric incinerators and many fluidized bed incinerators use venturi scrubbers only. In a typical combination venturi/impingement tray scrubber, hot gas exits the incinerator and enters the precooling or quench section of the scrubber. Spray nozzles in the quench section cool the incoming gas and the quenched gas then enters the venturi section of the control device. Venturi water is usually pumped into an inlet weir above the quencher. The venturi water enters the scrubber above the throat and floods the throat completely. This eliminates build-up of solids and reduces abrasion. Turbulence created by high gas velocity in the converging throat section deflects some of the water traveling down the throat into the gas stream. Particulate matter carried along with the gas stream impacts on these water particles and on the water wall. As the scrubber water and flue gas leave the venturi section, they pass into a flooded elbow where the stream velocity decreases, allowing the water and gas to separate.

Most venturi sections come equipped with variable throats. By restricting the throat area within the venturi, the linear gas velocity is increased and the pressure drop is subsequently increased. Up to a certain point, increasing the venturi pressure drop increases the removal efficiency. Venturi scrubbers typically maintain 60 to 99% removal efficiency for particulate matter, depending on pressure drop and particle size distribution. At the base of the flooded elbow, the gas stream passes through a connecting duct to the base of the impingement tray tower. Gas velocity is further reduced upon entry to the tower as the gas stream passes upward through the perforated impingement trays. Water usually enters the trays from inlet ports on opposite sides and flows across the tray. As gas passes through each perforation in the tray, it creates a jet which bubbles up the water and further entrains solid particles. At the top of the tower is a mist eliminator to reduce the carryover of water droplets in the stack effluent gas. The impingement section can contain from one to four trays, but most systems for which data are available have two or three trays.

**FUEL ECONOMY**

When dealing with incinerators, fuel is generally the most expensive part of the process from an operational standpoint. A ratio should be calculated beforehand that represents the amount of fuel used for the amount of sludge inputted. If there is a significant change to the amount of fuel consumed, it could mean that there is a problem in the fuel supply system, or air flow to the incinerator, or that an extensive furnace cleaning is in order.
COST CONSIDERATIONS

Minimal cost of operation and equipment maintenance is another economic parameter for sludge incineration. Preventive maintenance is the single most important factor in reduction of operating costs. Semiannual or quarterly appointments must be scheduled to allow time for complete furnace checkout and cleaning (referred to as "turnarounds"). Table 4 is a breakdown of the costs of each incinerator. Essentially costs can be related to one basic parameter: the lower the moisture content is in the sludge, the less expensive the incinerator will be to operate. Also, incinerators are bought based on what moisture level of sludge they are going to be effective with. Some incinerators can burn out sludge with 20% moisture levels and some cannot.

Table 4. Estimated Economics for Incineration.

<table>
<thead>
<tr>
<th>Type incinerator</th>
<th>Capacity (lbs/hr)</th>
<th>Sludge moisture content (%)</th>
<th>Installed cost (U.S. $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Hearth Furnace</td>
<td>7,000</td>
<td>0</td>
<td>11,000,000</td>
</tr>
<tr>
<td>Fluid Bed Incinerator</td>
<td>1,000</td>
<td>0</td>
<td>900,000</td>
</tr>
<tr>
<td></td>
<td>2,900</td>
<td>20</td>
<td>1,600,000</td>
</tr>
<tr>
<td>Electric Furnace</td>
<td>2,400</td>
<td>30</td>
<td>1,3000,000</td>
</tr>
<tr>
<td></td>
<td>2,400</td>
<td>0</td>
<td>950,000</td>
</tr>
<tr>
<td>Cyclonic Incinerator</td>
<td>2,000</td>
<td>20</td>
<td>1,000,000</td>
</tr>
</tbody>
</table>

The design cost will be a function of the incinerator cost plus installation, which is normally in the range of 4 to 7%. This cost should be doubled to include engineering services during project construction. It should be noted that with the electric furnace, the power needed to start up results in a large connected load. In areas of the country where there are high demand charges for electric power, this system can be economically impractical.
INDUSTRY APPROACHES TO SLUDGE VOLUME REDUCTION

When we think of sludge, what automatically comes to mind is sewerage. Water carriage systems of sewerage provide a simple and economical means for removing offensive and potentially dangerous wastes from household and industry. The solution and suspension of solids in the transporting of water produces sewage. Thus, the role of solids and sludge removal at sewage treatment plants is apparent. Sludge removal is complicated by the fact that some of the waste matters go into solution while others are colloidal or become finely divided in their flow through the sewage system. Ordinarily, less than half of such waste remains in suspension in a size or condition that can be separated by being strained out, skimmed off, or settled out. The remainder must then be precipitated out by chemical means, filtered mechanically, or be subjected to biological treatment whereby it is either removed from the water or changed in character so as to be rendered innocuous.

Sewage contains mineral and organic matter in suspension (coarse and fine suspended matter), in colloidal state (very finely dispersed matter), and in solution. Living organisms, notably bacteria and protozoa, find sewage to be an abundant source of food, and their lives' activities result in the decomposition of sewage. Sewage becomes offensive as a result of its own instability together with the objectionable concentration of suspended materials. In addition, the potential presence of disease-producing organisms makes sewage dangerous. Removal or stabilization of sewage matters may be accomplished in treatment works by a number of different methods or by a suitable combination of these methods. While sewage sludge is rich in nutrients and organic matter, offering the potential for applications as a biosolid (next chapter), or has a heating value making it suitable for incineration and possible heat or energy recovery, many industrial sludges are often unsuitable for reuse.

A more common practice with industrial sludge is to try and identify a reclaim value; i.e., if the sludge can be concentrated sufficiently there may be a portion of this waste which is reclaimable or can enter into a recycling market. If instead an enterprise can sell its waste, then some of the costs associated with waste management can be offset. For example, copper is a heavy metal and the sludge is a hazardous waste which is expensive to dispose of. Identifying an off-site recycling market that will take responsibility for this waste, even if they do not pay for it, can reduce or eliminate such costs as stabilizing and concentrating the sludge, as well as transport and tipping fees at the landfill. This option may not, however, eliminate the long-term liabilities associated with the waste if for some reason the reclamer has an incident in which the hazardous material impacts on a third party. Of concern, however, with any sludge management problem, are the
costs for recovery of potentially valuable by-products. There are many situations in industrial settings where large volumes of toxic sludges are generated on a continual basis. As with POTWs, waste management programs tend to focus on volume reduction techniques that reduce the costs for transport and disposal. The mechanical volume reduction techniques described earlier for wastewater treatment operations are equally applicable in these cases. But in some situations, thermal drying methods must be employed in order to achieve significant volume reductions, whether for disposal or reclaiming purposes.

Thermal techniques such as flash drying, the use of drying rooms, rotary kiln driers, and various other methods are costly. Ongoing energy costs as well as OM&R costs contribute to waste management programs. In many situations less passive drying techniques tend to be help reduce these treatment and recovery costs, such as the use of drying beds and lagoons.

The use of drying beds is one of two common methods of dewatering based upon passive thermal energy. Drying beds are generally used for dewatering of well-digested sludges. Attempts to air-dry raw sludge usually result in odor problems. Sludge drying beds consist of perforated or open-joint drainage pipe laid within a gravel base. The gravel is covered with a layer of sand. Partitions around and between the drying beds are generally open to the weather but may be covered with ventilated greenhouse-type enclosures where it is necessary to dewater sludge in wet climates. The drying of sludge on sand beds is accomplished by allowing water to drain from the sludge mass through the supporting sand to the drainage piping and natural evaporation to the air. As the sludge dries, cracks develop in the surface, allowing evaporation to occur from the lower layers which accelerates the drying process.

There are many design variations used for sludge drying beds, including the layout of the drainage piping, thickness and type of materials in the gravel and sand layers, and construction materials used for the partitions. The major variation is whether or not the beds are covered. Any covering structure must be well ventilated. In the past, some beds were constructed with flat concrete bottoms for drainage without pipes, but this construction has not been very satisfactory. Asphalt concrete (blacktop) has been used in some drying beds.

The only sidestream is the drainage water. This water is normally returned to the raw sewage flow to the plant or to the plant headworks. The drainage water is not normally treated prior to return to the plant. Experience is the best guide in determining the depth of sludge to be applied, however, typical application depth is 8 to 12 inches. The condition and moisture content of the sludge, the sand bed area available, and the need to draw sludge from digesters are factors to consider. It is not advisable to apply fresh sludge on top of dried sludge in a bed.
The best time to remove dried sludge from drying beds depends on a number of factors, such as subsequent treatment by grinding or shredding, the availability of drying bed area for application of current sludge production, labor availability, and, of course, the desired moisture content of the dried sludge. Sludge can be removed by shovel or forks at a moisture content of 60%, but if it is allowed to dry to 40% moisture, it will weigh only half as much and is still easy to handle. If the sludge gets too dry (10 to 20% moisture) it will be dusty and will be difficult to remove because it will crumble as it is removed. Many operators of smaller treatment plants use wheelbarrows to haul sludge from drying beds. Planks are often laid on the bed for a runway so that the wheelbarrow tire does not sink into the sand. Wheelbarrows can be kept close to the worker so that the shoveling distance is not great. Most plants use pick-up trucks or dump trucks to transport the sludge from the drying bed. Dump trucks have the advantage of quick unloading.

Where trucks are used, it is best to install concrete treadways in the sludge drying bed wide enough to carry the dual wheels since the drying bed can be damaged if the trucks are driven directly on the sand. The treadways should be installed so that good access is provided to all parts of the beds. If permanent treadways have not been installed, heavy planks may be placed on the sand. Large plants will normally utilize mechanical equipment for handling the dried sludge. Some communities have encouraged public usage of the dried sludge. In some cases users are allowed to remove the sludge from the beds, but this may not be satisfactory in many cases. Local regulations should be reviewed before attempting to establish a public utilization program.

The use of sludge lagoons is a technique that relies both on the settling characteristics of sludge and solar evaporation. The considerable labor involved in sludge drying bed operations may be avoided by the use of sludge lagoons. These lagoons are nothing but excavated areas in which digested sludge is allowed to drain and dry over a period of months or even a year or more. They are usually dug out by bulldozers, or other dirt-moving equipment, with the excavated material used for building up the sides to confine the sludge. Depths may range from 2 to 6 feet. Areas vary, and although drainage is desirable, it is not usually provided. Digested sludge is drawn as frequently as needed, with successive drawings on top of the previous ones until the lagoon is filled. A second lagoon may then be operated while the filled one is drying.

After the sludge has dried enough to be moved, a bulldozer, or a tractor with an end-loader, may be used to scoop out the sludge. In some locations it may be pushed from the lagoon by dozers into low ground for fill. Lagoons may be used for regular drying of sludge, reused after emptying, or allowed to fill and dry,
then leveled and developed into lawn. They can also be used as emergency storage when the sludge beds are full or when the digester must be emptied for repair. In the latter case it should be treated with some odor control chemicals, such as hydrated or chlorinated lime.

The size of the lagoon depends upon the use to which it will be put. Lagoons may take the place of sludge beds or provide a place for emergency drawings of sludge, but they may be unsightly and even unwanted on a small plant site. However, they are becoming more popular because they are inexpensive to build and operate.

Although lagoons are simple to construct and operate, there can be problems associated with sizing them. These problems largely arise from uncertainty in estimating the solar evaporative capacity. In semiarid regions evaporation ponds are a conventional means of disposing of wastewater without contamination of ground or surface waters. Evaporation ponds as defined herein will refer to lined retention facilities. Successful use of evaporation for wastewater disposal requires that evaporation equal or exceed the total water input to the system, including precipitation. The net evaporation may be defined as the difference between the evaporation and precipitation during any time period. Evaporation rates are to a great extent dependent upon the characteristics of the water body. Evaporation from small shallow ponds is usually considered to be quite different from that of large lakes, mainly because of differences in the rates of heating and cooling of the water bodies because of size and depth differences. Additionally, in semi-arid regions, hot dry air moving from a land surface over a water body will result in higher evaporation rates for smaller water bodies. The evaporation rate of a solution will decrease as the solids and chemical composition increase. Depending upon its origin, evaporation pond influent may contain contaminants of various amounts and composition. Decreases in evaporation rates compared to fresh water rates can seriously increase the failure potential of ponds designed on fresh water evaporation criteria. Designers of settling ponds and lagoons that rely on evaporation need to know the probability level of their designs being exceeded. Confidence limits for published evaporation normals have not been given, nor have analyses been made of the effects of uncertainty in the estimated normals or of the temporal variation of net evaporation. Definition of the spatial and temporal distribution of parameters such as evaporation and precipitation is difficult in mountainous regions. A concern is that the application of many of the empirical equations, based on climatological data, for estimating evaporation has not been thoroughly tested for high-altitude conditions. In particular, the ability of these equations to define the variability of evaporation is basically unknown. Historically, pan data are the most common means for defining free water
evaporation. However, the density of evaporation pan stations is much less than that of weather stations.

Many methods exist for either measuring or estimating evaporative losses from free water surfaces. Evaporation pans provide one of the simplest, least expensive, and most widely used methods of estimating evaporative losses. Long-term pan records are available, providing a potential source of data for developing probabilities of net evaporation. The use of pan data involves the application of a coefficient to measured pan readings to estimate evaporation from a larger water body. Among the most useful methods for estimating evaporation from free water surfaces are the methods which use climatological data. Many of these equations exist, most being based directly upon the method which was originally intended for open water surfaces, but is now commonly applied to estimates of vegetative, water use.

Monthly evaporation estimates can be made using the Kohler-Nordenson-Fox equation with a pan coefficient of 0.7. The Kohler-Nordenson-Fox equation describes evaporation as the combination of water loss due to radiation heat energy and the aerodynamic removal of water vapor from a saturated surface. The general form for the combination equation is:

\[ E = \frac{d}{(d+y)} R_n + \frac{Y}{(d+Y)} E_a \]

where \( E \) is the evaporation in inches per day, \( d \) is the slope of the saturation vapor pressure curve at air temperature in inches of mercury per degree Fahrenheit, \( Y \) is the psychrometric constant in inches of mercury per degree Fahrenheit, \( R_n \) is the net radiation exchange expressed in equivalent inches of water evaporated, and \( E_a \) is an empirically derived bulk transfer term of the form:

\[ E_a = f(u) (e_s - e_a) \]

Where \( f(u) \) is a wind function and \( (e_s - e_a) \) is the vapor pressure deficit. Kohler-Nordenson-Fox evaluated the aerodynamic term using pan data resulting in the form:

\[ E_a = (0.37 + 0.0041U_p)(e_s - e_a) \]

where \( e_s \) is in units of inches of water per day, \( U_p \) is the wind speed 2 feet above the ground expressed in miles per day, and \( e_s \) and \( e_a \) are the saturation vapor pressures at mean air and mean dew-point temperatures, respectively (expressed in inches of mercury). For development of the wind function, an adjustment in the psychrometric constant is generally made to account for the sensible heat conducted through the sides and bottom of the evaporation pan. One may also
apply as an approximation the following expression for the psychrometric constant:

\[ Y = 0.000367P \]

where \( P \) is the atmospheric pressure in inches of mercury. My own experience in designing surface lagoons and evaporation ponds over the years, and substantiated in the literature, has been to apply a pan coefficient of 0.7.

Of concern is that very little information often is available concerning the effects of common wastewaters on evaporation rates. As noted, the evaporation rate of a solution will decrease as the solids and chemical concentrations increase. However, the overall effects on evaporation rates of dissolved constituents as well as color changes and other factors of wastewater are largely unknown.

Evaporation from surface ponds is usually based upon estimates of annual net evaporation. Calculation of annual evaporation rates requires estimates during periods when the surface may be frozen. Most studies related to cold weather evaporation have been concerned with snow rather than ice. In general, the evaporation from a snowpack is usually much less than the amount of melting that occurs. Considering the large percentage of the annual evaporation which occurs during the warmer months and the overall uncertainties involved in estimates of evaporation from water surfaces, the amount of evaporation from frozen ponds during winter can reasonably be neglected in calculating annual evaporation. A more important consideration is the evaporation which occurs during winter from ponds which may remain unfrozen because of the introduction of warm wastewater. In these cases, water temperature will influence the evaporation rates. However, the low value of the saturation vapor pressure of the air above any water body will limit evaporation. Annual estimates of evaporation herein can be made by applying the Kohler-Nordenson-Fox equation throughout the year. Such estimates should provide near maximum possible evaporation estimates. For lined ponds, evaporation will be confined mainly to the water surface area. Evaporation from the soil and vegetation on the banks surrounding the pond should be minimal. However, for ponds which have appreciable seepage to the surrounding area, evaporation from this area will be dependent upon the type and amount of vegetation, as well as the moisture content of the upper soil layers. Methods for estimating evaporation and/or evapotranspiration in these instances are readily available, and you can find some of these studies and estimating procedures by doing a Web search.

If water losses from the surrounding area are a major component of the total evaporative losses of the pond, then soil moisture conditions will be expected to
be high. Under nonlimiting soil moisture conditions vegetative moisture losses are often defined as "potential" losses. Evaporative losses in this case would not be expected to differ greatly from free water evaporation. The literature recommends in fact that lake evaporation be used as a measure of potential evapotranspiration. Thus, for high soil moisture conditions, evaporation rates calculated for the water surface should be applicable to the surrounding area. The influence upon evaporation of vegetative growth within a pond is uncertain. The literature is inconclusive as to whether vegetation will increase or decrease evaporation compared to an open surface. It appears that the effect may be somewhat dependent upon the size of the water body. Literature studies indicate vegetation will decrease evaporation for extensive surfaces with the effect being less for smaller surface areas. It is very possible, however, that the introduction of vegetation upon the surface of a water body of more limited extent may increase its evaporative water loss, but only while the vegetation remains in a healthy, robust condition. Thus, the effect of the presence of vegetation appears to range from being a water conservation mechanism to that of increasing evaporation. In either case, the potential effects appear to be quite large with reported ratios of vegetative covered to open water evaporation under extreme conditions ranging from 0.38 to 4.5. In most instances, this ratio would be expected to be much closer to unity.

Drying techniques based on passive thermal energy are still costly waste management programs because ultimately there are operating costs associated with the collection, transportation, and disposal of the dried waste. And in the end the long-term liabilities still persist, since there are waste materials that continue forever.

A SHORT REVIEW

Volume reduction techniques help to reduce the costs of disposal, but they are essentially treatment technologies. Among the range of technologies that are available, some are less costly in terms of operating costs and capital investments than others, but all of them contribute to the overall waste management dilemma of long-term liabilities since there is a final waste form that must be disposed of. Incineration as a technology is very expensive and carries many hidden costs that are associated with the required air pollution controls. When used in industrial applications, the ash is generally hazardous and costly to dispose of. Even in situations where resource recovery may be possible through a volume reduction technique, the investment needs to be examined carefully to assess whether there are long-term financial benefits and reduction of future and long-term liabilities.
RECOMMENDED RESOURCES


33. Performance Test Report for the Incineration System at the Honolulu Wastewater Treatment Plant, Honolulu, Oahu, Hawaii, [STAPPA-ALAPCO/05/22/86-No. 11], Zimpro, Rothschild, WI, January 1984.

34. Air Pollution Source Test. Sampling and Analysis of Air Pollutant Effluent From Wastewater Treatment Facility - Sand Island Wastewater Treatment Plant in Honolulu, Hawaii, [STAPPA/ALAPCO/05/22/86-No. 11], Ultrachem, Walnut Creek, CA, December 1978.

35. Air Pollution Source Test. Sampling and Analysis of Air Pollutant Effluent from Wastewater Treatment Facility - Sand Island Wastewater Treatment Plant In Honolulu, Hawaii - Phase II, [STAPPA/ALAPCO/05/22/86-No. 11], Ultrachem, Walnut Creek, CA, December 1979.


37. Metropolitan Sewer District - Little Miami Treatment Plant (three tests: August 9, 1985, September 16, 1980, and September 30, 1980) and Mill Creek Treatment Plant (January 9, 1986), [STAPPA/ALAPCO/05/28/86-No. 14], Southwest OH Air Pollution Control Agency.

38. Particulate Emissions Compliance Testing, At the City of Milwaukee South Shore Treatment Plant, Milwaukee, WI, [STAPPA/ALAPCO/06/12/86-No. 19], Entropy, Research Triangle Park, NC, December 1980.


40. Stack Test Report--Bayshore Regional Sewage Authority, In Union Beach, New Jersey, [STAPPA/ALAPCO/05/22/86-No. 12], New Jersey State Department of Environmental Protection, Trenton, NJ, March 1982.

41. Stack Test Report--Jersey City Sewage Authority, In Jersey City, New Jersey, [STAPPA/ALAPCO/05/22/86-No. 12], New Jersey State Department of Environmental Protection, Trenton, NJ, December 1980.
42. Stack Test Report--Northwest Bergen County Sewer Authority, In Waldwick, New Jersey, [STAPPA/ALAPCO/05/22/86-No. 12], New Jersey State Department of Environmental Protection, Trenton, NJ, March 1982.

43. Stack Test Report--Pequannock, Lincoln Park, and Fairfield Sewerage Authority, In Lincoln Park, New Jersey, [STAPPA/ALAPCO/05/22/86-No. 12], New Jersey State Department of Environmental Protection, Trenton, NJ, December 1975.


49. Sludge Incinerator Emission Testing. Unit No. 1 for City of Omaha, Papillion Creek Water Pollution Control Plant, [STAPPA-ALAPCO-10/28/86-No. 100], Particle Data Labs, Ltd., Elmhurst, IL, September 1978.

50. Sludge Incinerator Emission Testing. Unit No. 2 for City of Omaha, Papillion Creek Water Pollution Control Plant, [STAPPA-ALAPCO-10/28/86-No. 100], Particle Data Labs, Ltd., Elmhurst, IL, May 1980.

51. Particulate and Sulfur Dioxide Emissions Test Report For Zimpro on the Sewage Sludge Incinerator Stack at the Cedar Rapids Water Pollution Control Facility, [STAPPA/ALAPCO/ 11/04/86-No. 119], Serco, Cedar Falls, IA, September 1980.


