PDHonline Course C449 (5 PDH)

Thermal Processing of Biosolids

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Thermal Processing of Biosolids

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COURSE CONTENT

Assisted by the massive construction grant program of the Water Pollution Control Act, a large number of primary and secondary municipal and industrial wastewater treatment plants were brought on-line in the United States during the period 1970 to 1990. The plants generate large quantities of waste solids. Indeed, treatment technology for wastewater has two fundamental branches (1) the branch that converts the pollutant materials in the wastewater to carbon dioxide, nitrogen and/or water vapor through biological oxidation and (2) process steps (including both chemical precipitation and the conversion of dissolved pollutants to biomass) that convert pollutants to separable solids (biosolids). These biosolids include several waste streams:

- Primary Sludge
- Biological ("secondary") Sludge
- Advanced Wastewater Treatment Sludge; and
- Other Treatment Plant Solids (screenings, grit, scum)

Management of these waste solids and, more specifically, the three sludge types can be effected by many means. Here, we consider the thermal processes: drying and incineration and, briefly, the preparatory steps of mechanical dewatering and handling/feeding. These topics are preceded by a brief summary of the physical and chemical characteristics of the sludge solids.

This course assumes a basic understanding of chemistry and mathematics. It presumes basic engineering analysis perspectives but, through text and examples guides the student an understanding of the processes and interactions of sludge drying and burning systems. The course includes:

- The basic characteristics of biological sludge;
- The alternatives and characteristics of sludge dewatering, and feeding means;
- Sludge drying technologies; and
- Sludge incineration technologies.

A. Sludge Nature, Origins & Characteristics

The biological treatment of wastewater from domestic and many industrial sources involves a series of process steps aimed at either converting undesirable soluble pollutants from a dissolved state to a solid form or removing solids from the bulk flow. The majority of the pollutant mass that enters the plant exits the wastewater treatment plant as a constituent of various settled sludge streams collectively known as "biosolids".

The categories of biosolids include:

> *Primary Treatment Sludge* - the sludge generated through settling of suspended solids early in the treatment sequence. The sludge produced usually contains 3 to 7 percent solids which can be easily increased by thickening or dewatering;
>
> *Secondary Treatment Sludge* - the excess biomass generated in the activated sludge tanks under aerobic conditions through biological reproduction and growth whereby soluble pollutants (those that exert biochemical oxygen

demand denoted B.O.D.) are converted into biological cell mass. Secondary sludge has a low solids content (usually from 0.5 to 2 percent solids) and is more difficult to thicken and dewater than primary sludge; and

Tertiary Treatment Sludge - biomass generated in advanced wastewater treatment such as nitrification and denitrification to achieve superior effluent quality. Common treatments include biological or chemical precipitation for nitrogen and phosphorous removal.

Other solid streams are often generated in the course of treatment though in lesser quantities than the sludge: "scum" (the floatable material accumulating on clarifiers), "screenings" (the rags, twigs and other large solids screened from the entering wastewater) and "grit" (the coarse sandy/silty solids removed following screening). The quantity of such sludge generated in the course of wastewater treatment has been estimated at 48.75 metric tons (dry) of primary sludge per thousand cubic meters of wastewater subjected to primary treatment and 49.47 metric tons (dry) of secondary sludge per thousand cubic meters of wastewater treated by the activated sludge process.

Having captured the solids, some plants move directly to some kind of ultimate disposal system such as landfill or direct land application. Most plants interpose one of several processes ahead of disposal in order to accomplish several ends: pasteurization or other step to kill-off pathogenic organisms and "stabilization" of the sludge such that continued vigorous biological activity stops or is slowed. Common processes to accomplish these ends include lime addition and anaerobic digestion.

Lime addition involves mixing lime (calcium oxide or CaO) with the sludge to raise both the temperature (from the heat of hydration/slaking) and pH to kill pathogenic organisms and stop biological activity. This often involves addition of 20 to 30% lime (CaO by weight on dry solids) so a considerable increase in both mass and ash content occurs.

Digestion involves continuing biological degradation of organic compounds bound in the sludge under aerobic conditions (with excess oxygen) or, more commonly under anaerobic conditions (oxygen deficient). The latter generates fuel values as "digester gas" that have application as a fuel in incineration as well as for digester heating. Conversion of a portion of the biomass to fuel gas (the digester gas is about 50% methane and 50% CO_2) results in depletion of the fuel value of the sludge solids and adversely impacts the dewatering characteristics of the sludge.

The means for ultimate disposal of wastewater treatment solids has evolved over the years. For wastewater treatment plants that are in or near to rural areas with easy access to farmlands and that generate sludge having low concentrations of the heavy metals mercury, cadmium, chromium, lead and nickel, application of liquid sludge (2 - 5 percent solids), dried sludge products or composted sludge to croplands has been encouraged by many regulatory authorities and found to be cost-effective and generally acceptable to the sludge users. In more urbanized areas where the distance to and scale of land application would be unreasonable and/or where intensive industrialization has led to the presence of significant concentrations of heavy metals in the sludge, incineration followed by ash landfilling is often practiced.

The characteristics of wastewater treatment sludge are strongly related to (1) the mix of domestic, commercial and industrial wastewater types involved and (2) the process flowsheet of the treatment plant. Some communities use "combined sewers" where runoff from storm drains pass through the same sewer system as the sanitary sewage so that proportions between sewered contaminants and the mix of inert, soil-derived materials and vegetation (leaves, twigs etc.) that is scoured from the sewer lines during high storm flows is dependent on rainfall patterns. Changes and upsets in the treatment plant can significantly alter the characteristics of treatment and the performance of dewatering equipment. Therefore the characteristics of wastewater sludge are exceedingly variable and flexibility in the ability to respond to changes is an important process feature of a satisfactory sludge incineration system.

1. Sludge Composition

The solids in sludge fall into two broad categories: the combustibles and the ash. Combustibles include the organic cell mass and other organic matter (scum, leaves etc.). The ash component of sludge includes the relatively inert inorganic materials associated with the wastewater flow (grit, silt and sand etc.) but also includes the insoluble toxic metal compounds which can be environmentally significant.

2. Sludge Properties

a. Chemical Properties

The chemistry of biosolids differs significantly from that of most other wastes from its nature. Biomass is comprised, very importantly, of myriad microscopic organisms thus tending to enhance the phosphorous, nitrogen and, to a degree, the sulfur content in comparison to typical "refuse" materials. Also, the proclivity of biological organisms to ingest and store in their fat bodies or cytoplasm toxic elements and compounds (such as mercury, PCBs, and dioxin), can give organisms from some wastewater streams a problematic chemical makeup as it affects incineration and associated air pollution control and/or ash disposal requirements.

Data showing the range of basic sludge chemistry and heat content are shown in Table 1. This table is not an exhaustive compilation and very different sludge compositions will be found depending on the wastewater source and treatment methods [1].

Table 1. Thermal and Chemical Characteristics of Biosolids

Sludge Type	No. Data Points	Volatile Matter	Fixed Carbon	Ash	C	H	O	N	S	HHV Kcal/kg (dry)
Grit	3	35.5%	3.7%	54.0%	25.0%	3.2%	9.7%	0.7%	1.0%	3,042
Raw Primary + Secondary	69	59.4%	6.6%	34.4%	37.0%	5.2%	16.6%	3.7%	0.9%	3,790
Raw Secondary	1	58.8%	2.6%	38.6%	36.8%	5.4%	14.4%	3.8%	0.7%	4,000
Screenings	2			7.4%						3,500
Scum	9	79.8%	3.0%	17.2%	66.5%	9.8%	5.2%	0.7%	0.5%	8,043

The Table 1 data include several of the conventional wastewater plant products. Volatile matter, fixed carbon and ash are parts of the *proximate analysis* (see Fundamentals of Combustion – Part 1 course) and the elements carbon, hydrogen, oxygen, nitrogen and sulfur (the *ultimate analysis*) are the dominant elements important in contributing to the energy content shown as the higher heating value (HHV).

b. Physical Properties

Percent Solids and Dewatering. The percentage of solid matter is the most important sludge parameter in the design and operation of incineration systems. For most municipal treatment plants (often referred to in the United States as Publicly Owned Treatment Works or POTWs), dewatering steps are seldom able to produce a sludge with more than a 25 to 27 percent solids cake. Thus, the burning of sludge is more the "burning" of water than of organic biomass

The dewatering of sludge can be affected by a number of technologies. Table 2 indicates the range of performance of such equipment. One must remember in considering such generalizations on dewatering performance that biological sludge is a collection of living organisms. As such, it can be "young" or old, sickly or healthy, highly aerobic and vigorous or devoid of oxygen (septic) and in decline. Also, the same treatment plant can, from time to time, experience wide swings in dewatering performance due to changes in wastewater characteristics, temperature changes, plant process upsets, equipment malfunctions etc.

Table 2 Typical Sludge Dewatering Effectiveness Levels

Gravity Settling	**% Solids**	**Mechanical Dewatering**	**% Solids**
Clarifier	0.5 – 4	Vacuum Filter	14 – 23
Thickener	3 – 8	Belt Filters	16 – 34
Hydrocyclones	3 – 8	Filter Press (c/ lime/FeCl$_3$)	40 – 45
		Centrifuge (conventional)	14 – 23
Special Type		Twin-roll nip press	15 – 25
Sludge Drying Bed	85+	Centrifuge (high “g”)	23 – 35

To assist in gravity or mechanical dewatering, a variety of coagulation and/or conditioning aids may be used. These include alum, polymers, lime, lime and ferric chloride, and even recycled incinerator ash. For some of the filtering devices, precoats or filtering aids are sometimes used. While any or all of these may increase the percent solids, it is noteworthy with respect to the use of inorganic chemicals, that often a marginal improvement in cake percent solids is obtained with an increase in Energy Parameter (see below under Thermal Properties) and, thus, becomes less energy-efficient as a feed to combustion systems due to the dilution of sludge combustibles with inert matter.

Biology. The particular species of biological organisms in wastewater sludge may be important. Of particular importance are the pathogens (disease causing organisms) which could result in operational problems and hazards and/or limitations in disposal (pasteurization or other treatment may be required by regulatory agencies in order to effect a pathogen kill).

For most biological sludge, anaerobic organisms are present. On standing, available oxygen is rapidly consumed within the sludge mass by the aerobic species. Diffusion of atmospheric oxygen is too slow to renew it. Therefore, after an induction period, the anaerobic organisms begin to thrive and, in a short time, achieve dominance within the sludge mass. This can rapidly cause odor problems during storage due to generation of hydrogen sulfide and a spectrum of mercaptans and organic sulfides and disulfides. Other biological composition factors include the physical nature of the biota. For example, high fractions of filamentous bacteria, for example, tend to “bulk” the sludge, inhibiting dewatering effectiveness.

Heat of Combustion. The heat of combustion of sludge combustible is roughly comparable to that of peat. The overall heat of combustion is increased by the presence of oils and greases. In the sanitary engineering literature, sludge heat content is often reported in units of kcal/kg volatile solids (VS). However, this is may not provide quantitative insights with respect to energy balances since the VS content can be significantly different than the combustible content due to a high calcium and/or ferric hydroxide content.

The heat of combustion of wastewater sludge can be estimated from the ultimate chemical analysis of the sludge using the estimation methods described in Part 1 of the Combustion Fundamentals course. However, comparison of predictions using these relationships with data from fuels laboratories for a set of over 80 sludge samples from a variety of wastewater plants showed that these equations predict high. A modification of the Dulong Equation for application to sludge that, on average, predicts low by only about 6% develops the moisture, ash-free (MAF) heat of combustion by:

$$\text{kcal/kg} = 5{,}547\ C + 18{,}287\ H - 1{,}720\ O + 1{,}000\ N + 1{,}667\ S + 627Cl + 4{,}333\ P \qquad (1)$$

where: C, H, S etc. are the decimal percents of carbon, hydrogen, sulfur etc. evaluated on a dry, ash free basis.

The heat of combustion can be expected to vary over time and vary significantly for different biosolids types as shown in Table 3.

Table 3 Typical Higher Heating Value for Biosolids (kcal/dry kg)

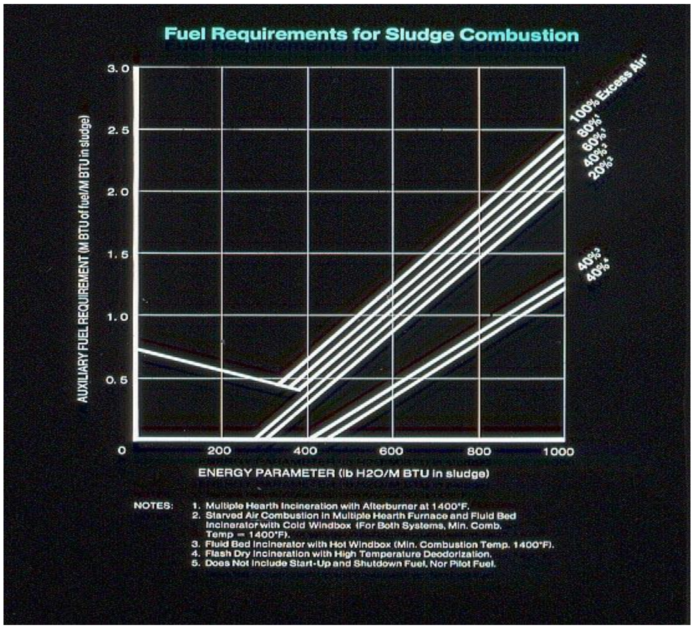
Sludge Type	HHV	Sludge Type	HHV
Raw Primary	5,500-7,000	Grease/Scum	9,250
Waste Activated	3,700-5,500	Fine Screenings	4,300
Digested Primary	3,050	Ground Garbage	4,550
Raw Primary + $FeCl_3$-lime	3,900	High Organic Grit	2,200
Trickling Filter	4,700-5,500		

Energy Parameter. In comparison to many other combustion systems, the sludge incinerator must cope with a fuel having an exceptionally high ash and moisture content. Thus, the balance between the fuel energy in the combustible, the burdensome latent heat demand of the moisture and the dilution effect of the ash is especially important and powerful. Often, thermal studies are inevitably conducted where the percent solids is carried as the independent parameter. It is both inconvenient and aggravating that the use of "percent solids" as a correlating variable (1) produces non-linear plots and (2) does not represent a sludge property that truly is a measure of quality. That is to say, it is not always beneficial to increase percent solids (as, say, through adding an inorganic sludge condition aid). A more useful variable for such investigations is the "Energy Parameter" (EP) which combines in a single term the heat and material balance for the combustion of sludge or other fuels or wastes. The EP is calculated as follows:

$$\text{EP} = \frac{(1-\text{S})\text{x } 10^6}{\text{S} \bullet \text{B} \bullet \text{V}} \ \text{kg H}_2\text{O per million kcal} \qquad (2)$$

Where:
S = decimal percent solids
V = decimal percent volatile solids
B = heat of combustion (kcal/kg volatile solids)

The EP collapses the heat effects of water evaporation, flue gas heating and waste-derived energy supply into a single term. Using the energy parameter, for example, fuel requirement and steam-raising potential for sludge incineration correlate linearly. Further, a reduction in EP is always a benefit: less fuel is always needed or more energy recovered. Figure 1 shows the relationship between the net auxiliary fuel requirement and the Energy Parameter of the sludge feed.



NOTES:
1. Multiple Hearth Incineration with Afterburner at 1400°F.
2. Starved Air Combustion in Multiple Hearth Furnace and Fluid Bed Incinerator with Cold Windbox (For Both Systems, Min. Comb. Temp = 1400°F).
3. Fluid Bed Incinerator with Hot Windbox (Min. Combustion Temp. 1400°F).
4. Flash Dry Incineration with High Temperature Deodorization.
5. Does Not Include Start-Up and Shutdown Fuel, Nor Pilot Fuel.

Figure 1 Sludge Incineration Fuel Requirement vs. Sludge Energy Parameter (English Units)

c. Materials Handling and Feeding

Many sludges can be pumped. However, the high pressure drop associated with sludge pumping requires that careful attention be given to estimation of the flow characteristics. Unless sludge has been dewatered, it can be transported most efficiently and economically by pumping through pipelines. Head losses must be estimated for sludge pumping, preferably using rheological data for the specific sludge of interest, since friction pressure drop behavior is often not the same as for water; especially for sludge of greater than 2 percent solids content. Head requirements for elevation and velocity, however, parallel those for water.

Water, oil, and most single-component, single phase fluids in laminar flow situations behave such that the pressure drop is directly proportional to the velocity and viscosity and that the viscosity is constant, independent of velocity (velocity being a measure of the shear rate in the fluid). The relationship between laminar flow pressure drop ΔP per length L of pipe of diameter D for a fluid of viscosity μ flowing at a velocity V is given by "Poiseuilles" law.

$$\Delta P = \frac{3.157 \times 10^{-7} \mu V L}{D^2} \qquad (3)$$

Where ΔP is the pressure drop (atm) over the length L (m) of pipe of diameter D (m) for a fluid of viscosity μ (centipoises) flowing at a velocity V (m/s).

As the velocity increases in a given flow situation, the flow behavior departs from purely laminar characteristics through a transition region where eddy formation increases in frequency and severity until a fully turbulent condition is attained. The onset of eddy formation is associated with the attainment of a Reynolds number (N_{Re} and dimensionless) of about 2,000 and fully turbulent flow is observed at $N_{Re} > 4{,}000$. N_{Re} is calculated (using consistent units) as:

$$N_{Re} = \frac{\rho_o \overline{u_o} d_o}{\mu_o g_c} = \frac{d_o G}{\mu_o g_c} \qquad (4)$$

Where, for example, the density ρ_o is given in $\text{kg}_{m\,/}\,\text{m}^3$, the mean velocity u_o in m/s, the characteristic dimension (diameter) d_o in m, μ in kg_f /s-m and g_c is a conversion factor equal to 9.806 kg_m- m/ kg_f -s^2 (32.2 lb_m-ft/lb_f -s^2 for English units, 1.0 g_m-cm/dyne-s^2 for cm-g-s units). Alternatively, one can calculate using G, the mass flow rate in kg_m/s-m^2.

For turbulent flow, the pressure drop ΔP (Pa) per length L (m) of pipe of diameter D (m) for a fluid of density ρ (kg_m /m^3) at a velocity V (m/s) is given by:

$$\Delta P = \frac{2 f \rho L V^2}{D g_c} \qquad (5)$$

The variable "f" (the "Fanning friction factor"), is a function of N_{Re} and pipe roughness. Note that a pressure drop of 1 kPa is equal to 10^4 dyne/cm^2 or 0.145 psi.

In flows of sludge, different behavior is observed. For wastewater sludge, the basic fluid behavior is "non-Newtonian:" viscosity is not constant. Such sludge, when placed in a rotational viscometer, shows thixotropic characteristics. In this type of viscometer, the test liquid is placed between two concentric cylinders; the central cylinder rotates. The torque on the outer cylinder is then measured as a function of rotational speed. When testing sludge, it is usually found that there is yield stress, (τ_o) below which the cylinder will not start to rotate. Then, as the rotational speed of the central cylinder (the shear rate) is increased, the resistance at first increases and then decreases. Such a reduction in apparent viscosity with shear rate is typical of thixotropy and results from the breakdown of physical structures and inter-particle attractive forces. This pattern of behavior is shown in Figure 2.

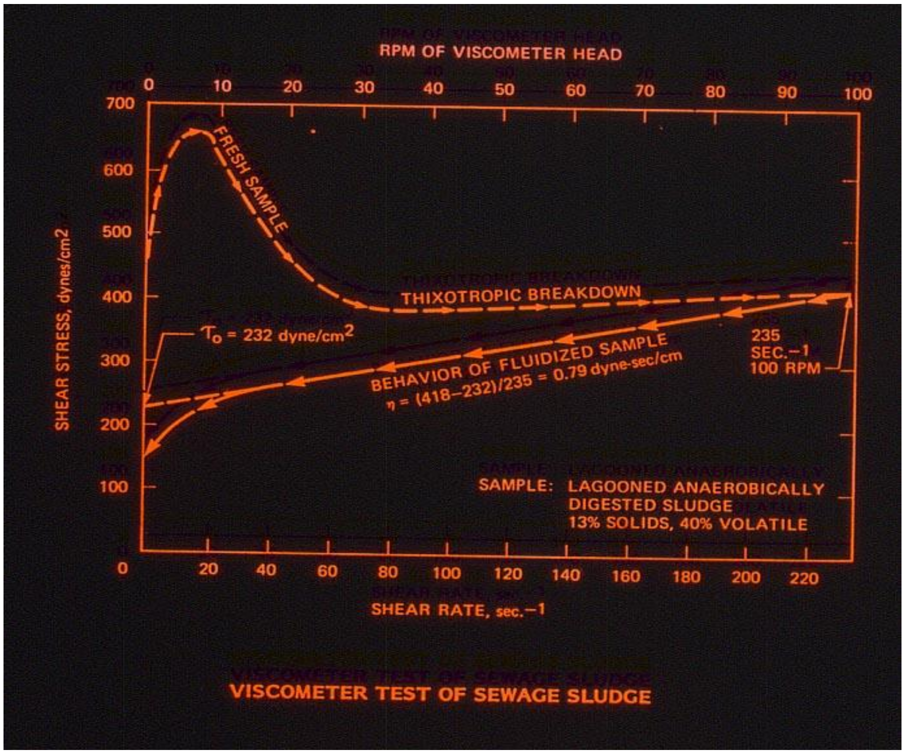


Figure 2. Viscometer Test of Sewerage Sludge (2)

Once these structures break down, one can develop an estimate of the fluid property which is akin to and has the same units as viscosity: the coefficient of rigidity (η). This flow behavior is known as that of a "Bingham plastic." To describe the pressure drop in such systems one must calculate the starting pressure needed to overcome the yield stress and the pressure to overcome friction. The starting pressure is given by:

$$\Delta P = \frac{4L\tau_o}{d_o} \qquad (6)$$

Note that the yield stress (τ_o) often increases with time as the material rests in the pipe in the no-flow situation. Thus, the start-up pressure requirement may be considerably greater than that calculated based on the (τ_o $\mathrm{kg_f/m^2}$) developed as shown in Figure 2. Since the development of such high yield stresses is time dependent, consideration should be given to purging the line (esp. the pump suction lines) if extended periods of no-flow are encountered.

To calculate the pressure drop for steady flow, two dimensionless numbers are used: a modified Reynolds number $N_{Re}{}'$ (using the coefficient of rigidity η_o instead of the viscosity) and the dimensionless Hedstrom number (He) given by:

$$N_{He} = \frac{d_o^2 \tau_o \rho_o}{\eta_o^2 g_c} \qquad (7)$$

Equation (5) can be used to estimate the pressure drop ΔP in atm for ρ_o in kg/m3, the length L in meters, the velocity V in meters/sec and using η_o in centipoises as the Bingham plastic limiting value (at high shear rate) for the coefficient of rigidity. The overall Fanning friction factor (f) in Eq. (5) should be developed as a function of the friction factor for laminar (f_L) and turbulent (f_T) flow by:

$$f = (f_L^{\,b} + f_T^{\,b})^{1/b} \qquad (8)$$

where f_L is the (iterative) solution to Eq. (9)

$$f_L = [\, 16/N_{Re'} \,][\, 1 + (1/6)(N_{He}/N_{Re'}) - (1/3)(N_{He}^{\,4} / f^3 N_{Re'}^{\,7})] \qquad (9)$$

with $$f_T = 10^a N_{Re'}^{-0.193} \qquad (10)$$

and where $$a = -1.47[1.0 + 0.146 \exp(- 2.9 \times 10^{-5} N_{He})] \qquad (11)$$

and $$b = 1.7 + 40{,}000/N_{Re'} \qquad (12)$$

An estimate of the friction factor can also be taken from Fig. 3.

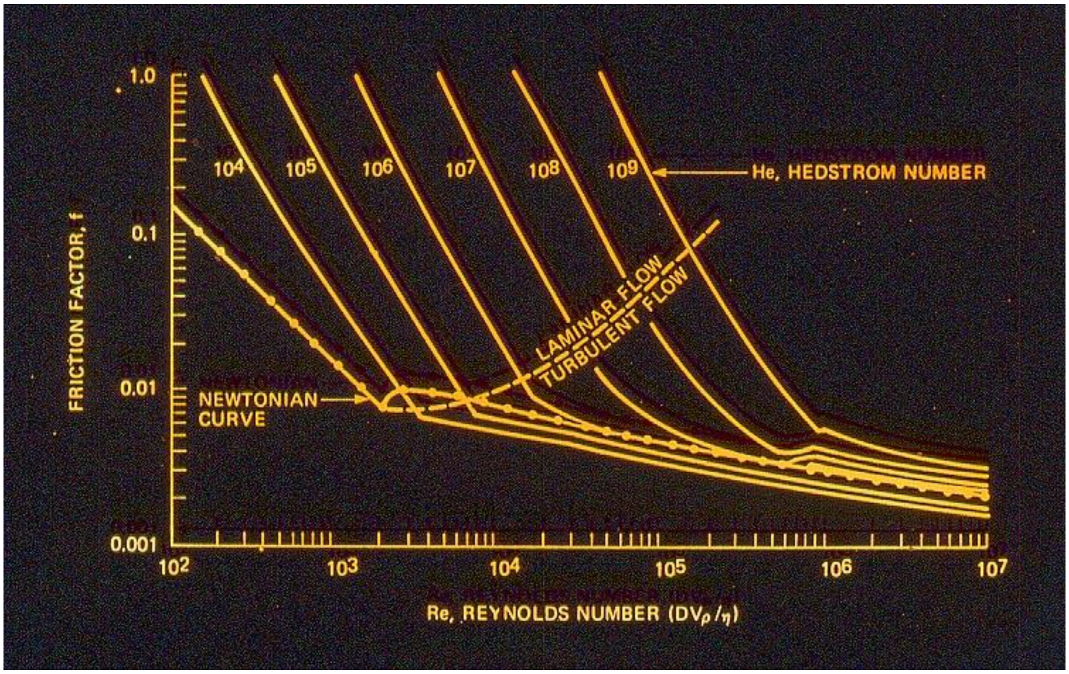


Figure 3 Friction factor for sludge analyzed as a Bingham plastic [2]

Progressing cavity (for relatively viscous sludge up to about 20 percent solids) or piston pumps (for the range of sludge solids content) have shown the best performance for wastewater sludge. The progressing cavity or eccentric screw pump transfers fluid by means of the progression of small, fixed cavities through the pump body as a central shaft rotates. The volumetric flow rate is proportional to the rotation rate. The nature of the impelling motion minimizes the shearing of the material being pumped and the flow from the pump incorporates little or no flow pulsing. At a given rotation rate, the pumping rate is constant and is insensitive to the back-pressure. Thus, use of a throttling valve to control flow rate is ineffective and, indeed, is likely to lead to excessive pressures and pump damage. To achieve flow control with a constant speed system, a bypass pipe ahead of a throttling valve allows adjustable recirculation to be used to modulate net forward flow. Figure 4 shows one of the more common progressing cavity pump designs.

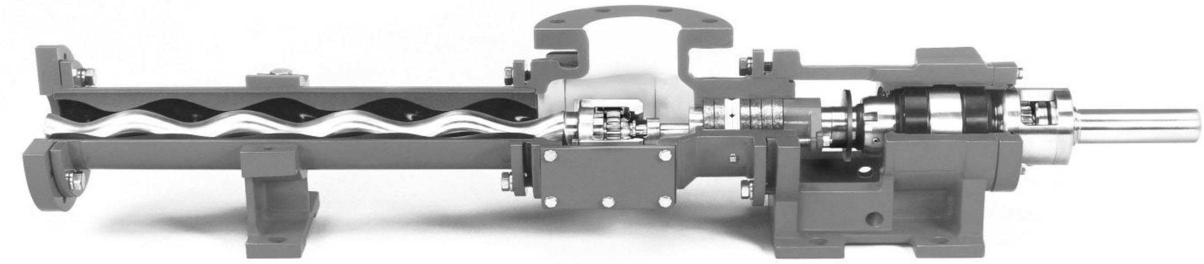


Figure 4. Progressive Cavity Pump (Courtesy of Moyno, Inc., a Unit of Robbins & Myers, Inc.)

Piston pumps are positive displacement (PD) pumps that use hydraulic drives to expel fixed volumes of sludge. Sludge pumps with rates to 3,800 l/min and pumping pressures to 240 bar gives considerable range to design and feed systems. The ability to develop such high discharge pressures allows such pumps to cope with significant elevation changes (gravity head) and long piping runs (friction losses) in the course of sludge transport and feeding. Sludge above 60% solids can be fed with such systems. This feed concept has particular importance for thermal processing systems (and, especially, combustion-based concepts) where the uniformity of feed rate couples strongly with the uniformity of the process itself: maintaining constancy in the air to fuel ratio.

The inherent nature of piston pumping results in significant pulsation in the flow rate. However, with appropriate design, the pulsing can be minimized. Figure 5 shows a piston pump commonly used in sludge applications. A screw feeder that force-feeds sludge into the pump is appended to the right. Figure 6, an exploded view of the pump, illustrates a common arrangement of the hydraulic and sludge cylinders and the poppet valves. Figure 7 shows the character of the extruded sludge mass that is generated by these pumps. When high percent solids sludge (say, above 35% solids) are injected into fluidized bed or multiple hearth incinerators, cutting blades are often mounted at the discharge point to halve or quarter the extruded sludge mass to facilitate subsequent in-process materials flow, sludge drying and more rapid initiation of combustion.

Figure 5. Positive Displacement (PD) pump (Courtesy of Schwing Bioset, Inc.)

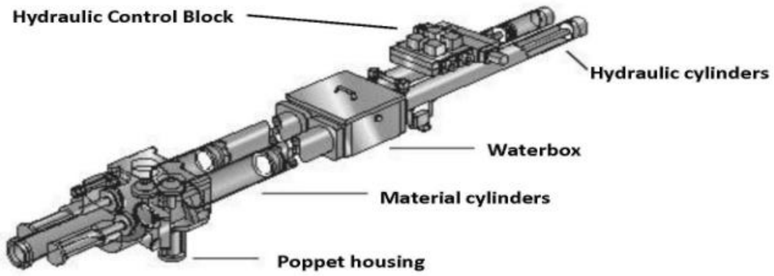


Figure 6. Exploded view of the Piston Pump (Courtesy of Schwing Bioset, Inc.)

Figure 7. Extruded High Solids Sludge from Piston Pump (Courtesy of Schwing Bioset, Inc.)

Belt conveyors using field vulcanized seams are simple and reliable and for semisolid sludge, can operate at up to an 18^o incline. Skirtboards are recommended at critical areas. Adjustable tension finger-type scrapers mounted beyond the idler on the flattened portion of the belt are recommended. Splashing and impact at transfer points should be minimized.

Screw conveyors are useful for sludge conveyance on the horizontal and, depending on the sludge consistency, up inclines. Abrasion resistant construction, provision for easy inspection and maintenance ingress are recommended. In most cases, internal, intermediate bearings are undesirable thus limiting the maximum conveyor length to approximately 20 feet.

Conveyance of dewatered sludge via belt, tubular and screw conveyors; slides and inclines, and elevators has been demonstrated. Because the consistency of the sludge is so variable, however, the design selected must consider performance under conditions widely variant from "average".

B. Sludge Drying

Communities have seen sludge pelletizing as a workable process concept where the marketability of the product has been demonstrated. Several treatment plants use the direct-fired rotary or tray dryer to produce a pelletized product. The Houston, Texas flash drying facilities produce a powdery product which also has been marketable (although less easily than the relatively dust-free and convenient pelletized product. Figure 8 illustrates the dramatic impact of drying on the volume of sludge requiring disposal.

Drying is sometimes effected ahead of incineration to augment mechanical dewatering to reduce or eliminate fuel requirements (e.g. at the Pittsburgh, PA wastewater plant where steam dryers reduce sludge moisture content ahead of fluidized bed incinerators). At the Hyperion plant in Los Angeles, the Carver-Greenfield multiple effect evaporation produces a bone-dry sludge powder that is subsequently incinerated in a two-step (first air starved and then fully oxidizing) fluid bed incinerator. Sludge drying also effects pasteurization of sludge to obtain pathogen kill. This may be of benefit when regulatory requirements impose sludge pasteurization as a precondition for land application end-use.

Some jurisdictions use drying to improve the physical properties of the sludge prior to landfilling. A plant in California is required to provide sludge at 50% solids. Since this level of dewatering is beyond the capability of mechanical dewatering

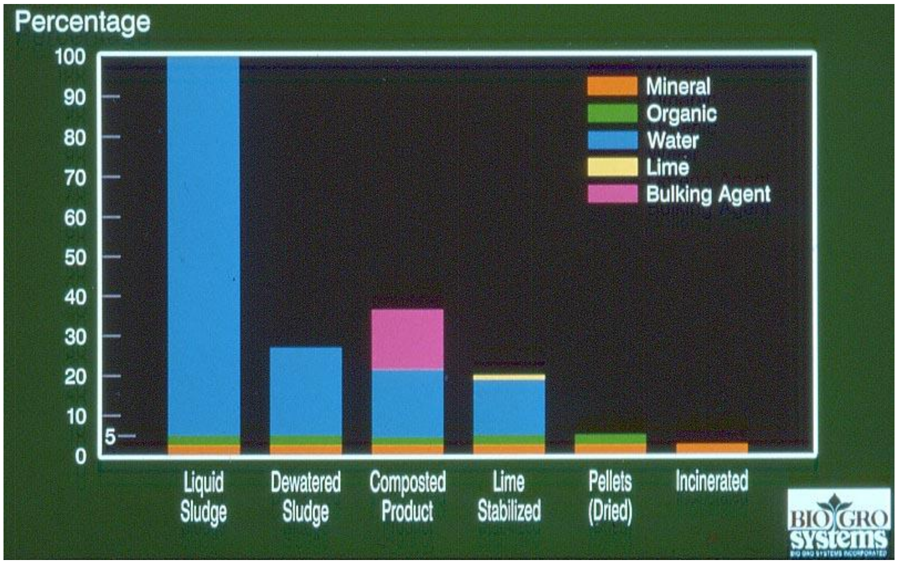


Figure 8. Impacts of Dewatering on Sludge Volume

and admixture with soil significantly increases hauling expense, drying may provide a better means to meet the landfill acceptance requirement.

The drying of sludge is effected in three basic modes:

Direct Dryers. Where the wet sludge is contacted with hot gases to effect evaporation. The primary technologies in this category are the Rotary Dryer and the Flash Dryer.

Indirect Dryers. Where the wet sludge is contacted with a hot surface to effect evaporation. The surface is usually heated by condensing steam but recirculating hot oil is also used. The primary technologies used are the toroidal, the hollow flight dryer, and the tray dryer. Thin-film scraped dryers can be used (e.g. in Dieppe, France) to partially dry thickened sludge from 6%-8% solids to about 20% solids but high energy cost and limited product dryness range limit applicability.

Special Processes The primary example of this category is a process wherein the wet sludge is combined with a oil carrier fluid and the water is evaporated in a multiple effect evaporator. This proprietary system (commonly known as the "Carver-Greenfield Process" after its inventors) is offered by Foster Wheeler under license to De-Hydro tech Inc. The R.E.S.T. process uses organic amine compounds which exhibit unusual solubility characteristics to effect separation of sludge solids but economic, hazard and performance problems have limited the development of the approach.

1. General Characteristics of Sludge Drying Systems

a. Energy Balance.

The energy cost for sludge drying is a key element of system operating costs. Since energy costs will probably escalate in the late 2000's, serious thought must be given to striking an optimum balance between the capital and operating costs for mechanical dewatering and those of drying processes.

The direct, indirect and multiple effect evaporation classes of dryers are each characterized by a relatively narrow range of thermal efficiencies. In general, the largest energy term is the heat of evaporation of the water. For direct dryers, the second largest term is the heat lost in the exhaust gases. The indirect dryers have essentially the same heat for water evaporation but lack the large exhaust gas sensible heat. This accounts for the roughly 25% higher energy for the direct systems. The special case of Carver-Greenfield (C-G) technology which exploits the unique high thermal efficiency of multiple effect evaporation (discussed below), leads to an extremely low relative energy use. However, the energy advantage of C-G is, at least partly, offset by the higher capital cost and significantly increased complexity of the facility.

b. Product/Process Characteristics

In most cases, sludge drying is carried out to generate a product. Thus, unlike "disposal" oriented process (e.g. incineration), drying operations must be sensitive to the receptiveness of the marketplace to the physical and chemical characteristics of their end product.

Physical Characteristics. Physical characteristics are of great importance for dried sludge products: uniformity of size and shape (affecting market value and blending characteristics) and dust content (affecting materials handling and end-user acceptability). The most desirable product size and shape is a uniform, spherical pellet with nominal 2-4 mm diameter and free of fibers, twigs etc. Pelletized sludge in this form is free flowing, can be easily augmented with synthetic nutrients and is more acceptable to the market.

Use of relatively simple and reliable pellet-forming steps (e.g. the "California Pelletizer") can be used following those processes which generate dusty products. Tests with such devices have been successful although the intrinsic strength and freedom from fines of the pelletized material is significantly lower than the "BB pellets" formed in the rotary and Pelletech processes.

ChemicalCharacteristics. The importance of chemical makeup is strongly related to the typical end-use of dried sludge as a soil amendment or low grade fertilizer. Consequently, high concentrations of heavy metals (cadmium, copper, mercury and lead are usually the "problem elements") can significantly degrade the marketability of the product; this is especially true for broad spectrum applications where the user is expecting little or no restriction on the crop involved. Heavy metal contamination has been a issue for Milorganite (cadmium) and is often raised as a deciding constraint in engineering evaluations of drying as a sludge management alternative.

To a lesser degree, the nitrogen-phosphorous-potassium (NPK) fertilizer assay of the dried sludge is important. Often, the principle value of the sludge is as a tilth-builder (improving the physical condition of soil relative to the ease of plant growth enhancing the "fluffiness" of the soil, so roots grow easily) rather than for its fertilizer value. Usually, less than 6% available nitrogen and small phosphorous and potassium values are found in the sludge especially for digested sludge. However, the fertilizer value is a base for amended products where quick release NPK values are added by a compounder to yield a balanced fertilizer with excellent soil-building characteristics.

Safety. In general, sludge drying processes are not high-risk. However, dry sludge is combustible and subject to "spontaneous combustion" (especially the fines) once the temperature has been raised above 175-250 °F . Initiation of the oxidative heat release which bootstraps dried sludge to combustion temperatures can come from thermophyllic composting activity instigated by wetting of the sludge.

Not infrequently, "situations" of escalating temperatures leading to fires and dust explosions are experienced by drying facilities (e.g. in Houston, Milwaukee and Tampa FL) which can drive the mass to the point where smoldering or full combustion occurs. The explosivity of fine sludge particles compounds the damage risk from self-generated ignition. Explosions of the dust aerosol in storage bins and silos can and has been observed. Secondary explosions can also occur where settled dust is suspended by a mild initiating explosion followed by a severe explosion of the suspended dust; commonly the primary cause of equipment loss and human injury. Considerable care to maintain sludge dryness along with provision of control protocols and facilities (e.g. the ability to move the sludge to break up heat generation, nitrogen purge systems explosion suppression equipment, good housekeeping discipline, attention to grounding of static charges and blow-out panels on silos) should be provided.

Environmental Impacts. In general, sludge drying facilities are environmentally benign and are often viewed as beneficial. However, care must be exercised in design and operation to avoid odor problems. These problems include both odors associated with the on-site receipt and storage of raw sludge and odors emitted from the drying process itself.

Odors with sludge receipt and storage are those typical of many sludge solids management facilities: sulfide-based odors (importantly hydrogen sulfide). These odors, though objectionable, are readily captured and controlled using hypochlorite scrubbers or soil filters.

Odors from the drying process itself are importantly related to the maximum temperature experienced by the sludge and the compounds volatilized from the sludge. Further, the ease of control is strongly influenced by he quantity of odorous gases produced. Thus, the direct drying alternatives where a large quantity of gas is contacted with sludge presents a more. challenging odor control problem than, say the multiple effect evaporation concept which only has small flows from vents.

2. Direct Dryers

Direct dryers include the class of dryer concepts where drying is effected by direct contact of hot gas with the wet sludge. The off-gas from direct dryers is generated (1) in large quantity (owing to the limited energy content of, say, a cubic meter of hot gas relative to the high latent heat of evaporation of water) and (2) is often odorous. The character of the odor depends on the temperature level of the hot gas stream. Gas fed to direct contact rotary dryers at 400-600 deg. F emerges with a typical, sulfide-based "sludge" smell. Experience has shown this odor is controllable with a conventional hypochlorite-type chemically oxidizing scrubber. At progressively higher high-end gas temperatures, the odor character shifts toward a "burnt protein" smell which includes numerous pyrolysis-derived aldehydes which are not well-controlled with scrubbers: afterburner control devices are required. For energy efficiency, a high-efficiency regenerative thermal oxidizer (RTO) afterburner design is preferred. In RTO units, the incoming cool gas is preheated by passing through a bed of hot refractory. Firing fuel then increments the temperature of the pre-heated gas to incineration temperatures (say, 1650°F). The burned-out exhaust gases then pass through a second refractory bed, preheating it. From time to time, the gas flow path is switched. The do, however, have a high capital cost and may experience problems with fouling of the refractory bed by carry-over of particulate matter.

a. Rotary Direct Dryers

The most common direct contact dryer system is the rotary dryer. Here, wet sludge is fed and hot gases passed either counter-current or co-current. A characteristic of biological sludge is the formation of a sticky consistency at about 40% solids. If this condition forms within the dryer, a “ring” will develop. Thus, the wet sludge from dewatering is often blended using a pug mill (Figure 9) with dry recycled fines and crushed over-size to “jump” over the 40% sticky zone.

The sludge is fed, then, at about 45-50% solids and dried. Figure 10 shows a typical system flowsheet. Single pass dryers are more common in Europe whereas, in the US, a triple-pass system is dominant. Flow of the solids in the single pass configuration is facilitated by sloping the dryer much as is done in a rotary kiln. For the triple-pass concept, the solids are moved by the air stream (thus, only co-current flow is possible). Also, for the triple pass system, since the motive action requires operation within a tight range of gas-to-solids relative velocity, the gas flow rate and system dimensions are more narrowly defined.

The solid product of the rotary dryer, elutriated from the dryer drum and captured in a large diameter cyclone. The spherical pelletized product is sized to the 4-6 mm diameter range using a double-deck screen. Undersize and (crushed) oversize are recycled and blended with the incoming wet sludge cake.

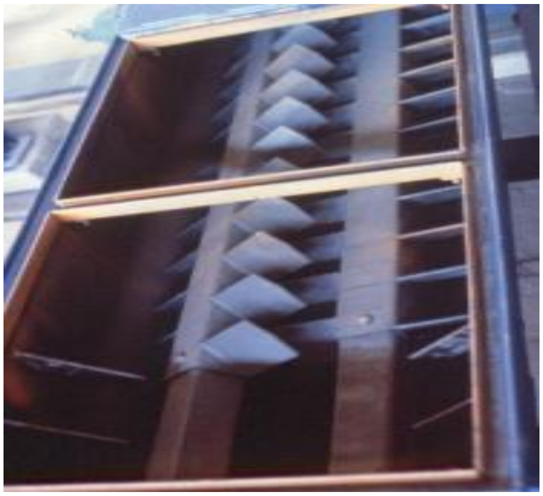


Figure 9 “Pug Mill” to Blend Dry and Wet Sludge to > 40% Solids

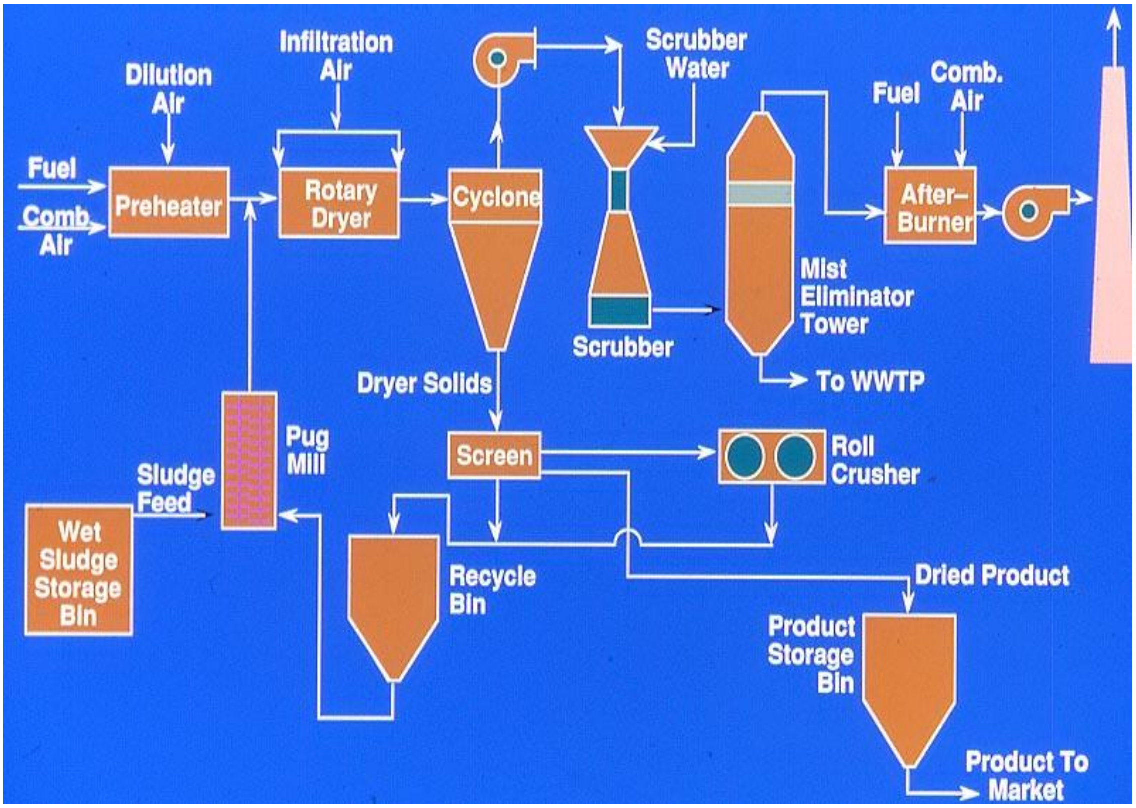


Figure 10 Rotary Dryer Flowsheet

The selection of inlet gas temperatures is driven by the heat balance on the dryer. A direct dryer system is sized by the gas flow since the evaporative capacity (for a given gas flow) scales directly to the temperature drop of the drying gas between the feed point and the discharge (typically, the discharge is at about 90°C). Thus, the capital cost per unit of productivity for the dryer drops as the inlet gas temperature increases. It is the play-off between the fall in dryer capital cost (and an increase in the thermal efficiency) as gas temperatures increases and the increased cost in pollution control (scrubber and afterburner) that sets the design point. Typically, the temperature is set in excess of 425°C.

b. Flash Dryer.

Flash dryer technology (Figure 11) effects sludge drying in the space of only a few seconds. In this device (see figure below), a blend of dewatered sludge and dry recycle (for the same reasons as for the rotary system) are injected into the center of a stoutly fabricated paddle wheel-type fan or “cage mill” which is moving a high-temperature gas stream. The mill blades break up the sludge and distribute it into the gas stream where, almost instantly, the water evaporates. The product solids are swept out of the mill and separated from the gases using a cyclone. A portion of the dry solids are recycled and the remainder constitutes the product: a powdery material. In some cases, the product is pelletized to enhance marketability (to reduce the dustiness of the unpelletized material).

The off-gas of the flash dryer has an intense and unpleasant odor and requires combustion (afterburner) type technology for control. A portion of the hot off-gas from the afterburner is recycled to the cage mill to provide drying energy and the remainder is scrubber (for particulate control) and discharged.

c. Tray Dryer.

Tray dryer technology (Figure 12) is offered by Seaghers in Belgium. Their “Pelletech” system uses a tray dryer heated both by passing heated oil through the trays and by passing hot gases over the trays. The blended sludge (as before) is dropped onto the top tray and moved to the periphery by plow-like devices that hang below radial arms that extend from a rotating, central shaft. At the periphery, the solids pass through “drop-holes” and fall to the next tray. On the tray below, the plows are oriented such as to move the material toward the center where they fall through an annular space to the next tray and so on. The product is a roughly spherical pellet. As for the rotary system, the product is screened to produce a narrow particle size range and overs and unders are recycled.

3. Indirect Dryers

Indirect dryers avoid the development of large volumes of odorous off-gas by heating the incoming sludge using a heat exchanger device. Steam or recirculated hot oil are used to apply heat to the incoming sludge (as before, blended to >40% solids to avoid the sticky behavior that will foul the heat transfer surface) and evaporate the moisture. The product is substantially dry (usually > 95% solids) and powdery.

In indirect dryers, a small air flow is maintained through the unit to sweep out the steam (about 10% of the steam weight flow). This highly odorous steam/ air stream is passed to an indirect or direct condenser and, usually, the final gas stream (small in volume) is incinerated for odor control. Note that the intense and foul odor of the off-gas is an inherent characteristic of indirect drying and effective, non-scrubbing (the chemistry of the odorant species are not well-controlled by hypochlorite scrubbing) odor abatement is mandatory. Often, the boiler used to generate the steam can use the purge air as combustion air thus economically effecting the afterburner function without new capital investment.

a. Disk Dryers.

The torus disk dryer (such as those by Stord or Bepex) passes the sludge through a steam heated cavity with a rotating shaft on which are mounted a series of hollow, steam-heated disks. (Figure 13) Small “plows” mounted on the periphery of the disks apply a gentle push to slowly move the sludge through the unit.

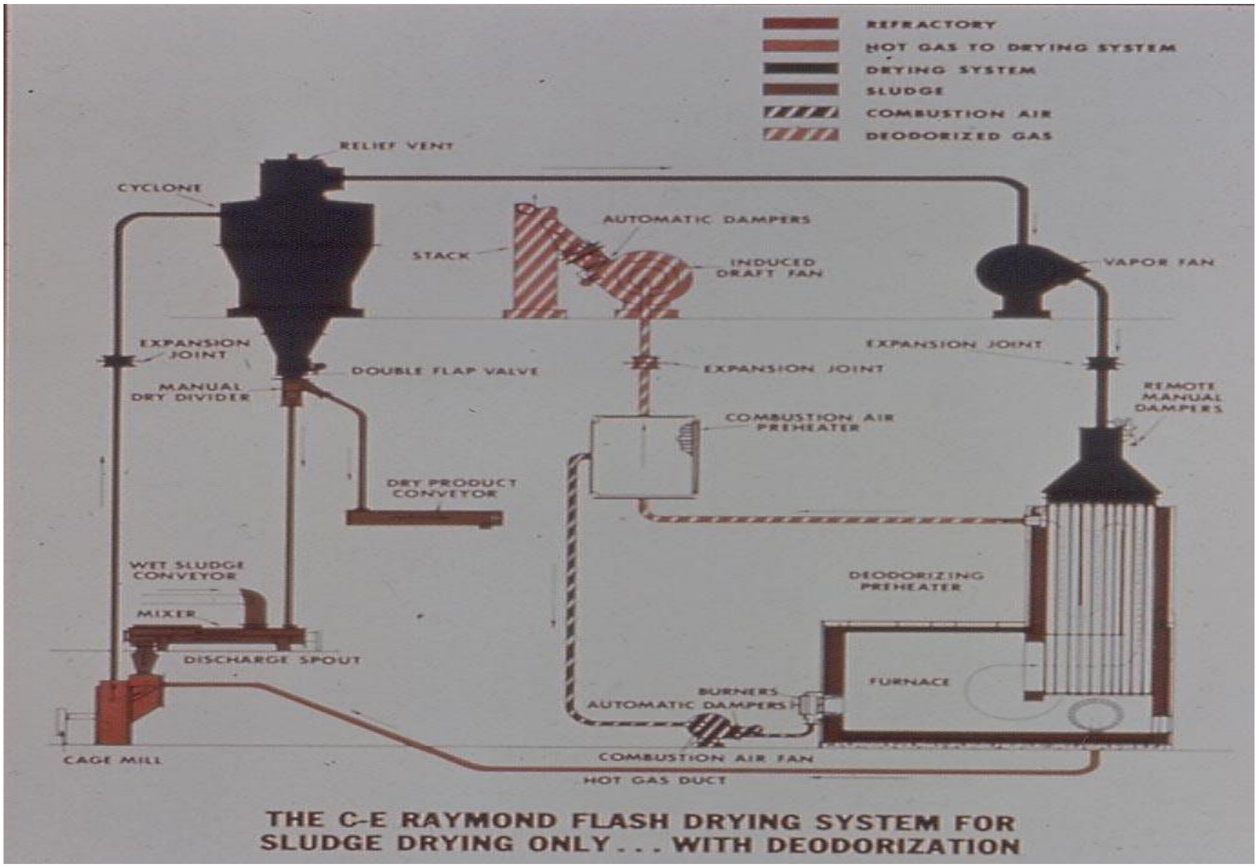


Figure 11 Flash Dryer Flowsheet

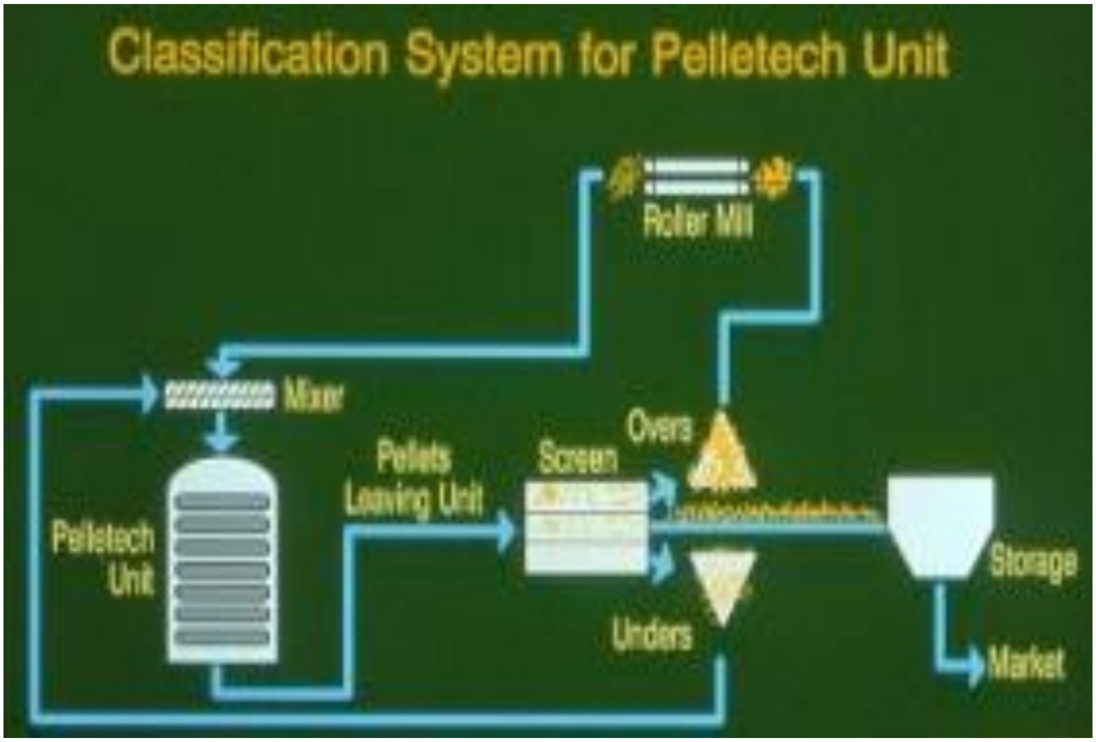
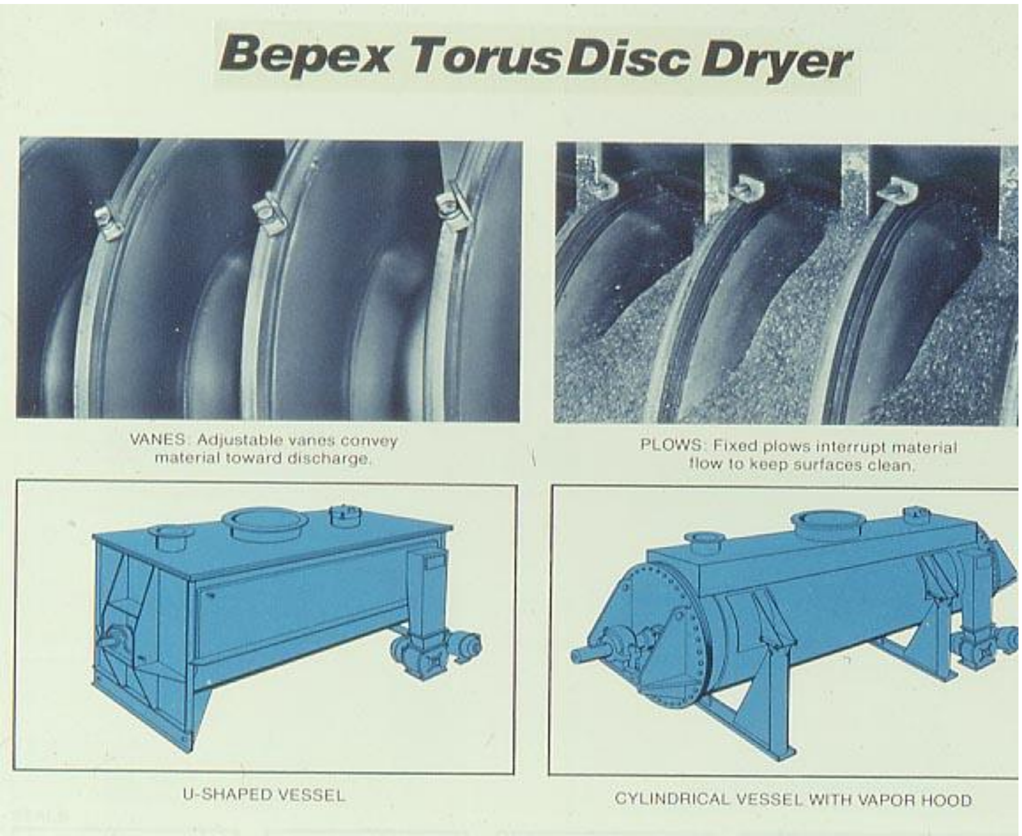


Figure 12 Pelletech Dryer Flowsheet



VANES: Adjustable vanes convey material toward discharge.

PLOWS: Fixed plows interrupt material flow to keep surfaces clean.

Figure 13 Bepex Torus Disk Dryer

Paddle Dryer. The Paddle dryer (by Komline-Sanderson and others) use twin banks of hollow paddles to heat and move sludge through their unit (Figure 14).

Figure 14 Komline-Sanderson Paddle Dryer

4. Special Processes

Carver-Greenfield. The Carver-Greenfield (C-G) process (named after its inventors) uses multiple effect evaporators (MEE) to dry sludge to >98% solids. In a MEE system, a kilogram of steam evaporates a kilogram of water in the heat exchanger from an evaporator stage by condensing in tubes surrounded by the fluid feed slurry. The steam from the this stage is passed to a condenser in the second stage where, in condensing, it gives up heat energy to evaporate a second kilogram of water . . . and so on. At each stage, the steam pressure (and temperature) drops and may require re-compression. The overall effect is that the initial kilogram of steam is seen to have evaporated more than one kilogram of water from the feed.

This contrasts to the conventional steam-heated dryers which evaporate only one kilogram of water per kilogram of steam condensed. One problem is apparent, however: if the feed contains solids (as does sewage sludge), as the feed dries it becomes more viscous and tends to build up as an insulating layer on the heat exchanger tubes. Eventually, the process grinds to a halt.

C-G solved this problem by adding oil to the sludge so the feed is a water-oil-sludge solids mixture and the output is an oil-sludge solids slurry which is still fluid. If one then centrifuges out the oil for recirculation, a dry sludge product is produced. Figure 15 shows the flowsheet for a triple-effect C-G system and Figure 16 shows the plant at the Coors brewery in Colorado where wastewater sludge from beer manufacture is dried with food-grade oils to produce a cattle feed product.

Dried C-G sludge is particularly prone to auto-ignition both because of the very fine particle size and the presence of residual oil. Spontaneous combustion events have occurred with the product.

5. Operability /Maintainability

Sludge drying facilities add an entirely new dimension to most wastewater treatment plants. New kinds of equipment, new operating constraints and hazards, new operating and maintenance skills are demanded. For the MEE system, the most complex of the systems discussed in this paper, the equipment is highly instrumented and satisfactory operation (reflected in product quality, equipment availability, maintenance costs etc.) is considerably more complex than most wastewater treatment processes. Indirect and direct dryers are simpler.

6. Concept Selection.

Each of the drying technologies has its pros and cons. The categories of differences include the relative energy efficiency, capital cost, product character (powder, pellets etc.), environmental emissions and the degree of technical development and demonstration. Selection between the alternatives is thus a relatively complex process involving a balance between the goals and constraints of the client and the system characteristics. Several key comparisons are summarized in Table 4.

C. Sludge Incineration

Sludge is significantly different from municipal solid waste in both chemical and physical properties. It is characterized by a very high ratio of water to solids. Its chemical makeup is predominantly carbon, hydrogen and oxygen and inorganic ash but includes significant fractions of phosphorous and nitrogen. From a health effects point of view, (with the exception of potential problems with pathogenic organisms and/or heavy metals) biological sludge is relatively benign. The cooling effect of free water, by greatly slowing the overall combustion rate, is a key process characteristic of these high-moisture materials.

The outer layer of sludge dries and chars on introduction into a hot environment. The ash and char layer insulate the surface; thus reducing the rate of heat transfer to the interior. The high latent heat of evaporation of water in the interior further extends the time required for complete drying and combustion. The net impact of these effects is that the sludge incinerator must either (1) provide effective means to manipulate or abrade the sludge mass to disturb and/or wear off the protective ash/char layer and expose the wet interior to heat or (2) provide an extensive solids residence time.

The primary application of the incineration technology for the management of wastewater treatment plant sludge involves the multiple hearth furnace (MHF) and the fluidized bed (FB). Rotary kilns are infrequently used for biological sludge. Kilns see their greatest application for some industrial wastes and for hazardous wastes (including the high heat content sludge) but their process characteristics make them poor candidates for sludge incineration service.

Because (most) sludge can be pumped, many of the problems of storing and feeding that are experienced with solid wastes are greatly simplified (although odor can be a severe problem after prolonged storage of biological sludge). The flow characteristics and small ash particle sizes of sludge make the use of a grate-type support during burning unacceptable. For this reason, sludge is burned on a hearth or in suspension.

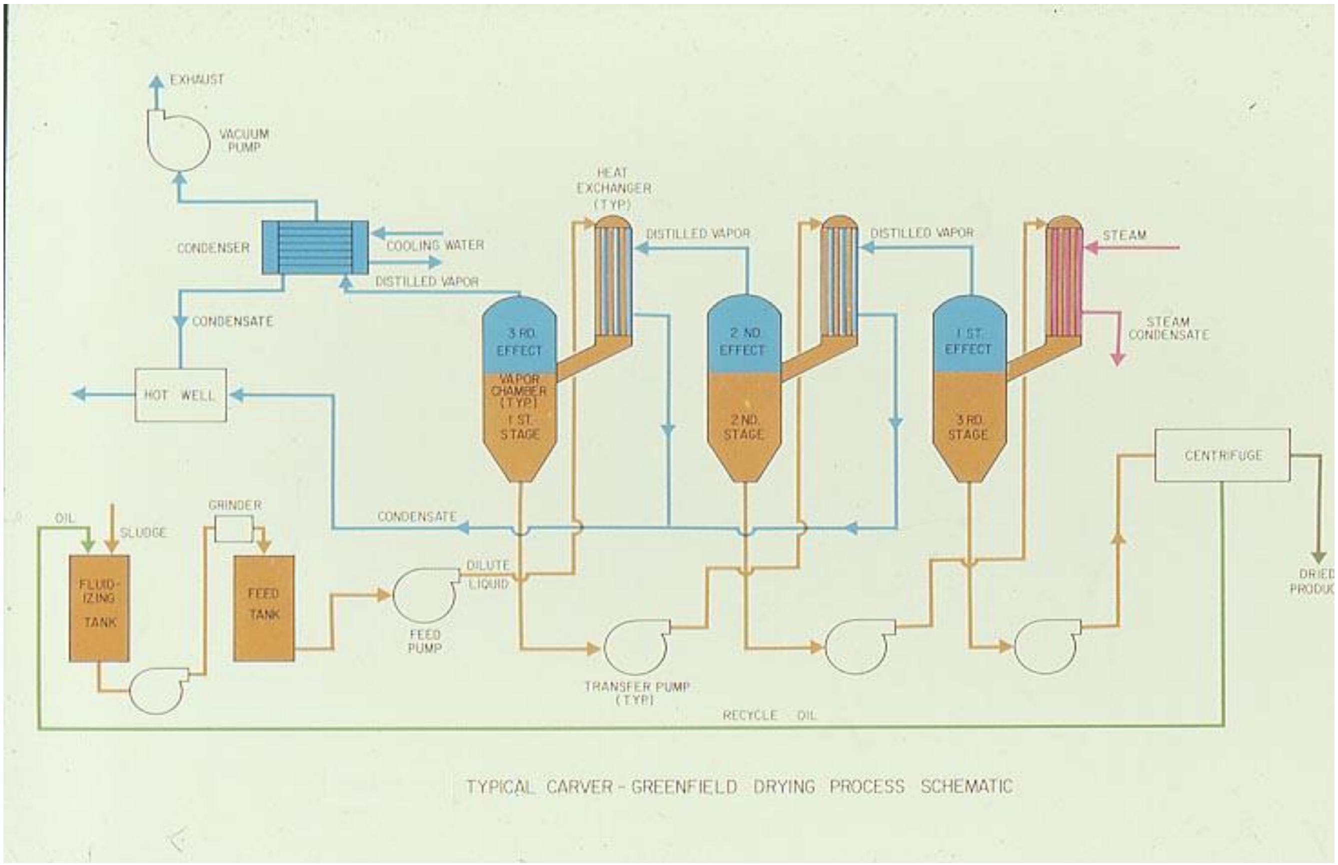


Figure 15 C-G Process Flowsheet

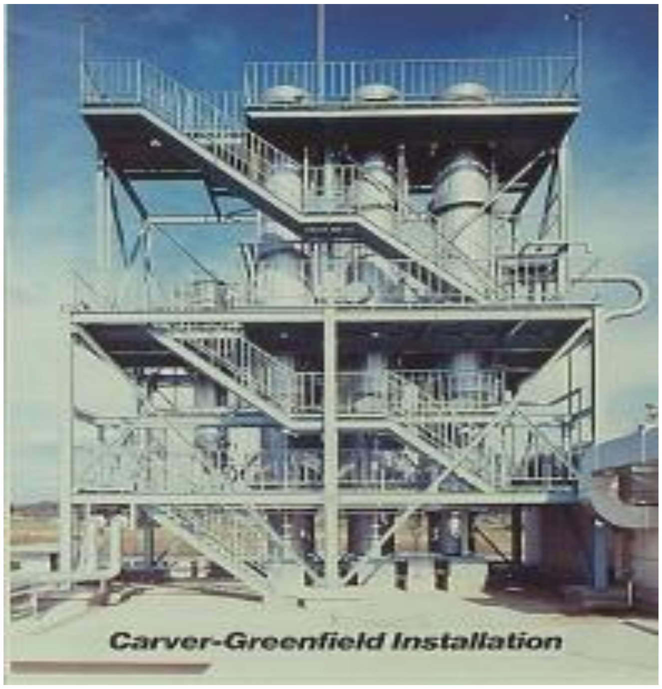


Figure 16 Coors System

-	-	-	-	Installations		Relative
	Energy	Process	Product		Europe &	Capital
Process	kcal/kg H_2O	Complexity	Nature	USA	Japan	Cost
Direct						
Rotary Dryer w/ Odor Scrubber	833	Medium	Pellet	Several	Several	Moderate
Rotary Dryer w/ Afterburner	1000	Medium	Pellet	Few	Few	Moderate-High
Flash Dryer w/ Deodorization	1222	Medium	Powder	Man	Few	Moderate
Indirect						
Steam Dryer	761	Low	Powder	Very Few	Several	Moderate-High
Tray Dryer	772	Low	Pellet	None	Very Few	Moderate-High
Special						
Carver-Greenfield	194	High	Powder	Very Few	Very Few	High

Table 4. Energy and Process Characteristics of Sludge Drying Alternatives

1. Fluid Bed (FB) Incineration

The fluid bed (FB) incinerator is well suited to the drying and combustion of a wide variety of sludge wastes. The fluidized bed furnace (FB), as applied in sludge incineration, is an inherently simple combustor (see Figure 17). Air at 3-5 psig is forced into the windbox at about 20-40% excess over the theoretical air requirement and passes into a cylindrical furnace through a refractory-lined grid or constriction plate. The plate may also be fabricated of alloy steels. Either includes an array of tuyers that pass the air into the bottom of the bed and minimize the leakage of sand into the windbox below. Resting on the constriction plate is a mass of graded sand (usually 20 to 80 mesh) about a meter deep. As the rate of air flow increases, the sand bed expands to about twice its original volume: sufficient expansion to expand the bed to a density high enough such that the sludge will not float to the top of the bed, yet not so much air flow as to blow the sand out of the reactor. The gas velocities under these conditions average between 0.7 and 1.0 meters per second. Additional details are given in Reference 1.

The sludge is fed directly into the bed using close-clearance, shallow flight extruder screws or coarsely sprayed onto the top of the bed is dried and abraded by the vigorous scrubbing action of the hot sand particles. Volatile organic are vaporized from the sludge and burn; mostly in the bed but partially in the freeboard space over the bed. Residence time of the gases is about 1 second in the bed and 2 to 3 seconds in the freeboard. Ash particles, if small, are blown out of the bed and, if large, accumulate in the bed and must be drawn off periodically. Sand losses are approximately 1 percent for each 60 hours of operation.

The top of the bed is relatively well-defined and the gas rising through the bed includes clearly defined gas bubbles. The hydraulic behavior of the fluidized bed is as though it held an ordinary liquid: solids with a lower density float; the upper surface is well defined and remains horizontal when the bed is tipped; the surface levels equalize when two chambers are interconnected; solids will overflow if the upper surface is higher than a drain point in the sidewall. This is the conventional, "bubbling fluid bed" mode of operation.

Above the fluid bed is a large, cylindrical disengaging space known as the freeboard. The freeboard usually provides about 3 to 4 seconds of residence time for final burnout of combustible material. The freeboard operates at or slightly above the bed temperature. The finely divided ash is swept out of the bed and collected in a scrubber or other air pollution control system. Coarse or heavy particles remain in the bed: either decrepitating with time and blowing out or requiring removal through a drain.

At a given time, only a small portion (usually less than one percent) of the bed mass is combustible matter. The large mass of the bed gives it thermal inertia so that the bed can absorb fluctuations in feed characteristics without the problematical upset conditions that affect the multiple hearth furnace (MHF). Solids or sludge fed into the bed or into the freeboard are rapidly heated by radiation and intense convection. The rapid heat and mass transfer between bed constituents results in high temperature uniformity. Typically, gas temperatures vary less than 5 to 8 °C between any one location in the bed and another.

Sludge cake that is introduced into the hot bed is abraded by the scrubbing action of the sand grains. The sludge particles rapidly dry and then burn, releasing most of their fuel value in the bed. A 5 to 8 cm diameter plug of sludge discharged into the bed requires 20 to 30 seconds to volatilize while more dispersed feeds may gasify within only a few seconds.

FBs were introduced for the combustion of sewage sludge in 1962. Although its application in the U.S. to date has been dwarfed by MHF installations, the energy efficient "hot windbox design" embodiment of the fluid bed is the system of choice in most new installations. This reflects the greater degree of control available and improved air emissions due to lower, more controllable temperatures (reduced NOx and heavy metal volatilization) and superior mixing (very low CO and total hydrocarbon emissions). Over 75 furnaces are operating in North America and many more in Europe. The capacities of fluid bed furnaces (in all services) range from 250,000 to 60 million kcal/hr and diameters from slightly over a meter to 15 meters.

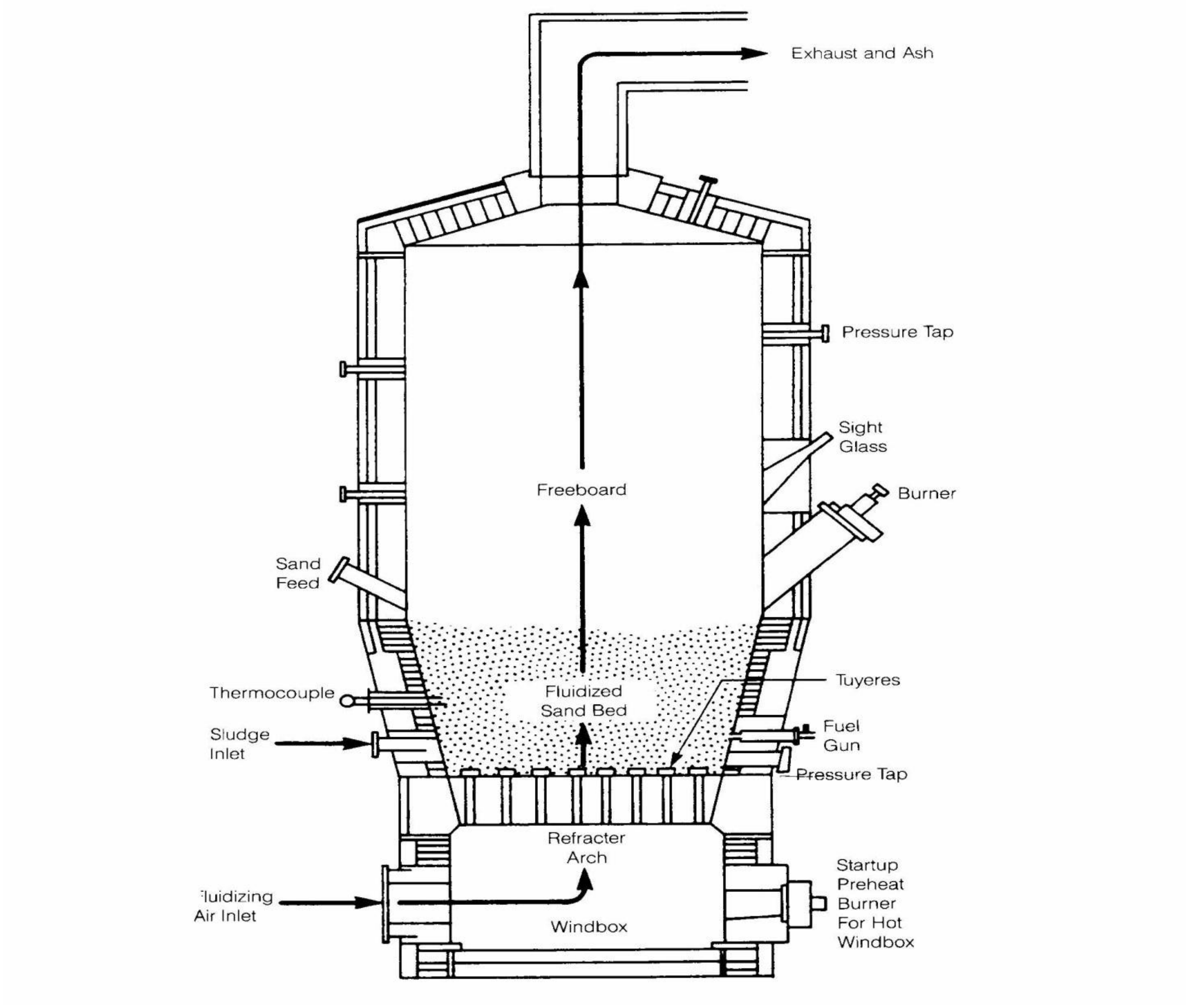


Figure 17 Fluidized Bed Incineration System

FB technology rapidly penetrated the sludge incineration market when fuel was relatively cheap. However, in the late 1970's as fuel costs rose steeply, there were severe cut-backs in the rate of construction of new FB installations and many existing units were shut down. The energy problem was, importantly, derived from two factors. First, the early FBs were simple, plug flow reactors. Without any regenerative heat feedback, the full price of the heat content corresponding to peak combustion temperatures was paid for with fuel. Secondly, the mechanical dewatering equipment in wide use (primarily, the vacuum filter) was not very effective so the evaporative energy demand was high. This combination made the FB very expensive to operate. The energy efficiency of the MHF, unencumbered with penalties (at that time) for hydrocarbon or carbon monoxide emissions, appeared attractive.

In response to the challenge of burgeoning energy costs, the vendor community developed a new, energy conserving modification, the "hot windbox fluid bed". Here, the hot off-gas from the freeboard is passed through a shell and tube heat exchanger to preheat the incoming combustion air. Initial designs heated the air to 500 °C but, in modern plants, reheat to 850 °C is achieved. Recycling heat substantially decreases the net fuel used in the FB.

FB waste incineration at 750 °C and 40% excess air is autogeneous at an Energy Parameter of 125-140 kg H_2O/MMkcal (225-250lb H_2O/MMBtu). As the feed becomes "hotter" (lower Energy Parameter) the temperature will rise. The maximum bed temperature is set partially by materials of construction, design features (ability of the structure - especially the grid plate - to accommodate the thermal expansion) or, most usually, the onset of problems with ash fusion, particle agglomeration, heavy metal volatilization and bed defluidization. For many sludge this sets an upper limit of about 850 °C.

As the feed Energy Parameter increases, one reaches a point where excess air cannot be reduced further and bed temperature has fallen to 730 °C ; the lowest practical temperature for combustion. At this point burners discharging into the bed can be used to maintain combustion conditions. Alternatively, the fluidizing air can be preheated by gas-to-gas heat exchange with the furnace exhaust gas: the so-called hot windbox FB configuration (Slide 29). Using hot windbox techniques with air preheat to an upper limit of about 550°C, waste with an Energy Parameter of 235 kg H_2O/MMkcal may be burned autogeneously (without fuel use).

Fluid beds are available in diameters ranging from 7 feet to as large as 53 feet. The largest bed now in operation for sludge incineration is about 21 feet in diameter at the freeboard although several 30-foot beds are under construction. The very large beds are primarily used for ore processing or petroleum refining.

Problem areas with the FB reactor primarily focus on (1) feed equipment (jamming, eroding), (2) local overheating of the sidewalls near feed injection or burner ports, and (3) bed defluidization or clinker build-up in the freeboard or ducts due to ash fusion or eutectic formation. The turn-down in fluid beds is somewhat limited since a relatively narrow range of air velocities provides adequate fluidization without undue sand loss. However, during periods when low feed is needed or over weekends, when maintenance on downstream equipment is required etc., the bed can be dropped for a short period (just turn the air fan off!), started up, shut down, etc. Because of the excellent heat retention of the collapsed bed, start-up is rapid and, also, fuel burning to maintain bed readiness over longer time periods is minimal. Further, the structurally simple refractory design allows such “up and down” operation without incurring catastrophic refractory spalling and collapse: a freedom in operating strategy not available with the MHF furnace.

2. Multiple Hearth

The multiple hearth furnace (MHF) is, perhaps, the most common incinerator for wastewater treatment sludge. This is importantly due to two features: (1) the countercurrent flow of wet sludge against the rising flue gases inherently provides energy recuperation for sludge drying and, (2) the furnace response to changes in sludge feed rate or feed moisture is automatic, safe and productive - the unit continues to function well.

The MHF (Figure 18) is the most widely used wastewater treatment sludge incinerator in the United States. The units consist of a vertical cylindrical shell containing from four to fourteen firebrick hearths. A hollow cast iron or steel shaft is mounted in the center of the shell. The center shaft is rotated at 0.5 to 1.5 rpm. Two to four opposed arms are attached to the shaft and are cantilevered out over each hearth. A series of wide, spade-like teeth are mounted on the arms. As the arm rotates, the sludge is plowed or "rabbled" toward the center (on an "in-feed hearth") or toward the outside wall (on an "out-feed hearth").

The center shaft and rabble arms are insulated with refractory and cooled by air forced through a central "cold air tube" by a blower (Figure 19). The air returns via the annular space between the cold air tube and the outer walls: the hot air compartment. The center shaft is provided with a rotating sand seal on the top and bottom to avoid infiltration of tramp air into the furnace.

Standard units can be purchased in diameters from 1.4 to 8.8 meters. The capacity of these furnaces ranges from 100 to 3600 kg/hr of dry sludge. Specifications with the details for furnaces used in the United States are found in relevant handbooks [1]. Each hearth has an opening ("drop-hole") through which the sludge falls from hearth to hearth. The drop-hole penetrations alternate in location from a wide clearance around the central shaft (on an "in-feed hearth") to spaced holes at the periphery (an "out-feed hearth"). The sequence is set such that the top hearth is usually fed at the periphery and the bottom hearth discharges at the periphery. The mean residence time of solids in the furnace is variable but approximates 0.75 to 1.25 hours.

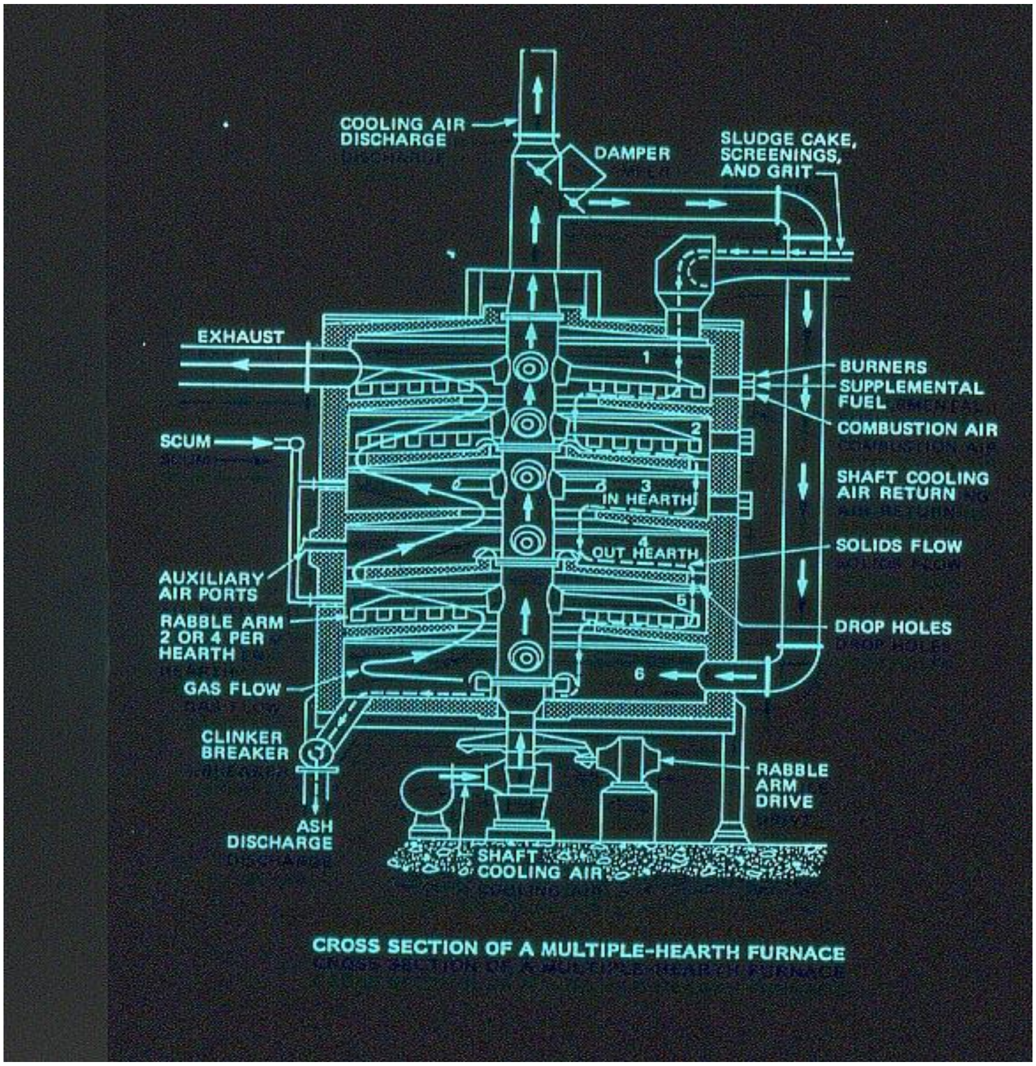


Figure 184 Multiple Hearth (MHF) Incineration System (2)

The rabbling process acts not only to move the sludge but also to cut, furrow and open the surface as it passes through the drying, burning or combustion zone, and cooling zone. Observations of the furnace show a significant "freshening" of the luminous diffusion flame rising from the sludge bed on passage of the rabble arm. The flame dies down to a flicker in only a few moments only to be rekindled with the passage of the next arm. The photograph in Figure 20 illustrates this dynamic process. The angle of the rabble teeth on the rabble arms is set to move the sludge toward the exit opening and to generate ridges thus increasing the effective exposed area to up to 130% of the plan area. An optimum rabble arm speed is where the width of the level portion in the valley of the furrows is approximately three centimeters. When rabble speed is too fast, this width will increase. When it is too slow, it will fill in with sludge. In some instances, the angle of the rabble teeth can be reversed (“back rabbling”) to increase residence time and to control the location of the combustion hearth. Back rabbling can about double the residence time on the hearth.

Attempts to "move the fire" by changing the rabble arm speed has the secondary effect of either building or stripping the inventory of sludge on the hearths. Excessive sludge inventory can lead to a runaway condition where relatively large quantities of sludge begin to burn at one time. This overloads the air supply and leads to smoking and excessive hydrocarbon emissions. As a generalization, the use of rabbling speed as a day-to-day operating parameter is unwise.

Commonly, each hearth is equipped with two access doors. The doors have fitted cast-iron frames with machined faces to provide a reasonably gas-tight closure. In circumstances where air inleakage is critical (e.g., starved-air combustion, activated carbon regeneration or charcoal manufacture), the doors may be gasketed and latched closed.

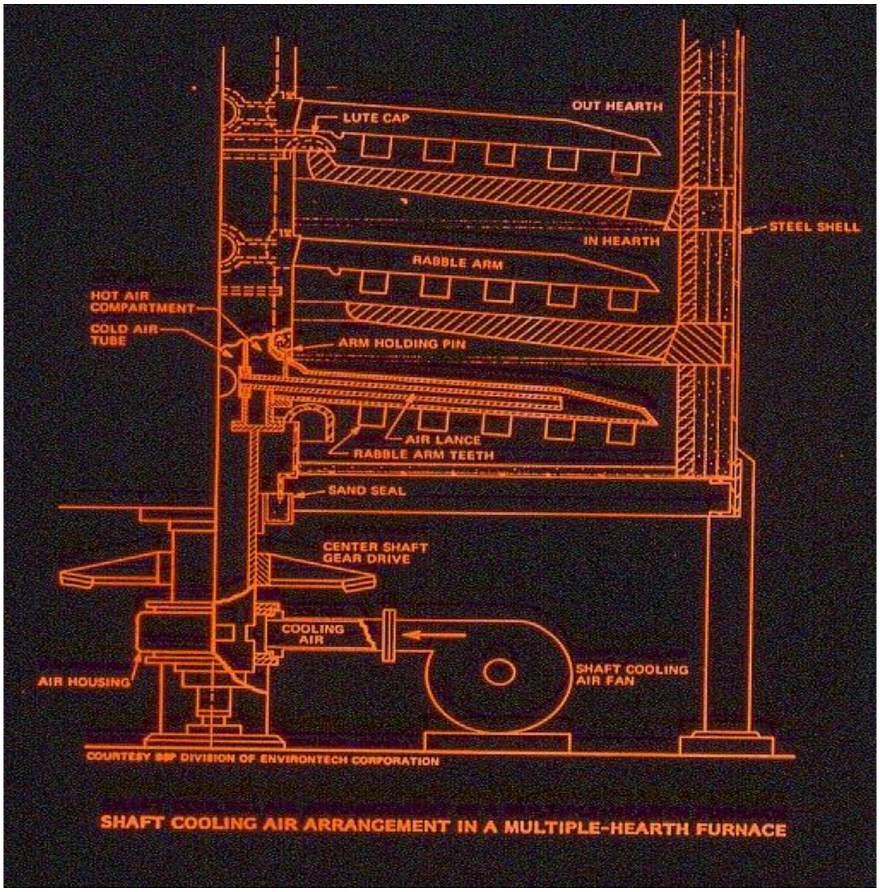


Figure 19 MHF Cooling Air System (2)

Figure 20 MHF Burning Pattern

Several of the intermediate hearths are equipped with burners supplied with natural gas or No. 2 fuel oil. The air for the burners is supplied at a high pressure such that the flame and the excess air are forcibly projected into the over-hearth volume. The air supplied through the burners typically supplies the air for sludge combustion. The overall excess air level used in multiple hearth systems varies widely. A good operator working with a feed system that supplies the sludge at a steady rate and consistent moisture content can run the units at 75-85% excess air. More typically, one finds the units operated at 100 to125% excess air. Highly irregular feed conditions and/or indifferent operation leads to excess air levels well over 125% with consequently excessive fuel and power consumption.

The temperature profile in the countercurrent sludge and flue gas flows depends on the relative magnitude of the following energy terms:

Sludge character and feed rate (moisture content, dry solids heating value, and ash content).

Combustion air quantities and temperature: In some units the warmed air from the hot air compartment (typically 120-175 °C) is used for combustion air. The unused arm cooling air is often blended with the exhaust gas from the scrubber to minimize the persistence of the visible plume. Also, the hearth doors leak some air.

Fuel firing rate: usually, the burners are provided on the upper and several lower hearths. Also, screenings, grease, and scum are often added to one of the lower hearths.

Heat loss from the outer shell.

In the idealized case, the temperature profile is as shown in Table 5.

In theory, the MHF can be operated without generating an odorous off-gas: little odoriferous matter is distilled until 80 to 90% of the water has been driven off (a sludge solids content of, say, 70%), and, at this point in the furnace, flue gas temperatures are high enough to burn out the odor. In practice, uncompensated for variations in sludge moisture and/or heat content, inattentive or untrained operators, inadequate mixing and/or residence time of odorous off-gas, and other factors occur with sufficient frequency to almost assure that odor will be a problem, at least from time to time. Protection from such problems and affirmative control of volatile organic compounds (VOC) emission includes the use of the top hearth as a secondary combustion chamber (with auxiliary fuel firing as needed) or installation of a separate external afterburner chamber.

Table 5 Idealized Temperature Profile in MHF Furnaces

	Drying Zone	**Burning Zone**	**Ash Cooling Zone**
Sludge	70 °C	739 °C	200 °C
Flue Gases	425 °C +	830 °C +	175 °C +

3. Air Pollution Control

Generally, the air pollution train following a fluidized bed or MHF system includes a Venturi scrubber for control of fine particulate matter (and heavy metals). In recent years, more costly wet electrostatic precipitator systems have been used to provide even higher particulate collection efficiency for plants with high heavy metal emission potential. Either of these alternatives is often followed by a tray scrubber acting both as a “mist eliminator” to capture carry-over water droplets and, with excess water flow, as a sub-cooler to reduce off-gas temperature so as to reduce or eliminate visible plume formation. These combinations bring incinerator technology into full compliance with the New Source Performance Standards (NSPS) [3] and heavy metal control requirements of the US EPA [4]. This latter issue, especially related to mercury control, presents significant challenges to the biosolids incineration community.

Additional detail on emission factors (kg emitted as related to design and operational parameters) and on the expected performance of alternative emission control technologies are presented in Reference 1.

E. Summary

This course has introduced you to the special problems and challenges of sludge management using thermal processes: drying and incineration. Drying produces an attractive and usable soil amendment with handling and transportation economics that allow the generating entity a reasonable marketing area. Incineration destroys the organic fraction of sludge to minimize landfill requirements and eliminate odor risk. Both process categories benefit from enhanced dewatering. Both categories require air pollution control but technology exists to readily meet all federal and state regulations.

F. References

1. Niessen, W., "*Combustion and Incineration Processes, Applications in Environmental Engineering* - 4th Ed.," Taylor and Francis Group, Boca Raton, FL, 2010

2. Process Design Manual for Sludge Treatment and Disposal, U.S. EPA, Municipal Environmental Research Laboratory, Office of Research and Development, Doc. No. EPA 625/1-79-011, September, 1979

3.U.S. EPA Standards of Performance for New Stationary Sources, Subpart O: Sewage Sludge Incinerators

4. 40 CFR, Part 503, Subpart E: Standards for the Use or Disposal of Sewage Sludge (Sections 503.40 et. seq)