MUNICIPAL WASTEWATER SLUDGE MANAGEMENT ALTERNATIVES

PREPARED FOR THE
ENVIRONMENTAL PROTECTION AGENCY
TECHNOLOGY TRANSFER
NATIONAL CONFERENCE ON
208 PLANNING AND IMPLEMENTATION

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SECTION I

INTRODUCTION

The following paper describes alternatives for the treatment and disposal or reuse of sludges resulting from wastewater treatment. There are several factors to keep in mind when planning a sludge handling system. The oft-quoted, "There is no such thing as a free lunch" is certainly applicable to sludge disposal or reuse. There has been no system demonstrated which produces useful by-products such as fertilizer or cattle feed that produces revenues which exceed processing costs. The revenues from by-products can recover portions of the processing costs.

Another important factor to consider is the variability of sludge characteristics between geographical areas and often within the same system. For example, two wastewater treatment systems in different locations may use identical processes but the sludge produced can vary in nature. Seasonal factors such as industrial waste loads from a cannery, can cause variations in a given system. Because of variability in characteristics, there is no universal solution to treating and disposing of sludges. The economics change from location to location as well as the environmental acceptance of alternative processes.

Another important factor relating to land disposal is the complication of adding one highly variable substance (sludge) to another (soil). Both substances are highly variable in terms of chemical characteristics, moisture contents and drainability, and trace element contents. Crops grown on sludge amended soil must be compatible with the soil and sludge used.

Additionally, the planner must carefully consider compatibility of various processes. For example, some chemical sludges may not be satisfactorily treated by anaerobic digestion.

The planner must have a basic understanding of the individual unit processes and the environmental restraints of his community and region to properly evaluate sludge management plans.

SECTION II

SIGNIFICANCE OF SLUDGE DISPOSAL ASPECT OF WASTEWATER MANAGEMENT

Implementation of wastewater management plans which result in higher degrees of wastewater treatment will result in improvements in water quality. Unfortunately, these improvements will be accompanied by the production of increasing quantities of increasingly difficult-to-handle sludges. For example, primary treatment of municipal wastewaters typically produces 2,500-3,000 gallons of sludge per million gallons (MG) of wastewater treated. When treatment is upgraded to secondary with activated sludge, the sludge quantities increase by 15,000-20,000 gallons per MG treated. Use of chemicals for phosphorus removal can add another 10,000 gallons per MG. The sludges withdrawn from primary treatment are as much as 97% water. Secondary and many chemical sludges have higher water contents and are much more difficult to dewater than primary sludges. A recent projection(1) of sludge trends in the U.S. indicates the magnitude of the problem:

	1972		1985	
Sludge Type	Population (Million)	Tons/Year (Million)	Population (Million)	Tons/Year (Million)
Primary	145	3.20	170	3.7
Secondary	101	1.50	170	2.5
Chemical	10	0.09	50	0.5
TOTAL		4.8		6.7

The cost of sludge handling and disposal is often greater than the cost of treating the wastewater itself. For example, the cost (capital, operation, and maintenance) of providing secondary treatment of 10 MGD of municipal wastewater may be 20-25 cents/1000 gallons, while the cost of disposing of the resulting sludges may be 30 to 100% (or more) of this amount. Another significant consideration is that although there may be several environmentally acceptable, technically feasible, and economically competitive methods for wastewater treatment in a given area, there may be only a few - perhaps only one - such sludge disposal alternatives. Thus, sludge disposal considerations are an important element in the selection of an overall wastewater management plan.

Regionalization of several smaller wastewater systems into a larger system may favorably affect the relative economics of some sludge disposal alternatives to the degree that they become economically feasible, whereas, they were not for any of the individual, smaller plants. For example, heat drying of sludge for use as a fertilizer decreases in cost by a factor of nearly 2 as plant capacity increases from 10 mgd to 50 mgd, while the cost of the anaerobic digestion process decreases only about 10%.

In some cases, integration of solid waste and wastewater sludge disposal plans may offer a useful, synergistic relationship. For a given population, the volume of solid wastes is about 10 times the volume of wastewater sludge. Thus, inclusion of sludge with solid wastes from an area may not significantly alter the volume of material to be handled in the solid waste system. For example, under certain conditions, disposal of dewatered, stabilized sludge may be readily compatible with an existing solid waste landfill practice. On the other hand, a sludge handling system would have to be altered drastically to have capacity for solid wastes. Such a plan could unfavorably affect an otherwise acceptable sludge handling plan. For example, a local market for compost might be ample for composted sewage sludge but might be overwhelmed by the much larger volume of a composting operation handling both sludge and solid wastes.

SECTION III

BASIC DISPOSAL ALTERNATIVES

Although a large number of alternative combinations of equipment and processes are used for treating sludges, the basic alternatives are fairly limited[2]. The ultimate depository of the materials contained in the sludge must either be land, air (by-products of incineration), or water. Current policies discourage practices such as ocean dumping of sludge as long term solutions. Air pollution considerations necessitate air pollution facilities as part of the sludge incineration process. Incineration results in a residual ash which must be disposed of. Thus, sludge in some form will eventually be returned to the land.

There are two basically different philosphical approaches in handling the sludges from wastewater treatment: reuse as opposed to disposal. The reuse approach is based upon recycling the sludges so that nutrients and organics contained in the sludges are beneficially reused. The goal of sludge treatment in this case is to make the sludge compatible with the proposed reuse system (i.e., stabilize the sludge so that it will not cause nuisance conditions, eliminate pathogens to prevent disease problems, etc.). The organic solids which make up 60-80 percent of the solids in a typical municipal sludge also are a potential source of energy (typically about 10,500 BTU/lb). Some processes discussed later in this paper convert these solids so that this energy can be beneficially reused. The disposal philosphy considers the sludge a waste material. In some cases, such as ocean dumping, limited pretreatment of sludge is provided prior to disposal. However, most disposal systems incorporate treatment techniques to provide maximum reductions in volume of sludge prior to disposal with little or no regard for the potentially beneficial components of sludge.

The choice between disposal and reuse approaches must be based upon the evaluation of the many factors (economics, environmental impacts, energy consumption, etc.) associated with each of the processes involved (as discussed in detail later in this paper). For example, the feasibility of recycling of sludges to the land for agricultural reuse is dependent upon the quality of the sludge, availability, location, use, nature, and cost of land. These factors may be a problem in some urban areas. Chicago transports a portion of its sludges to a site 160 miles downstate for application to previously strip-mined land indicating that under some circumstances transport to even relatively distant locales is practical.

Figure 1 summarizes general sludge handling alternatives. A recent EPA report[86] summarizes the current use of these various alternatives

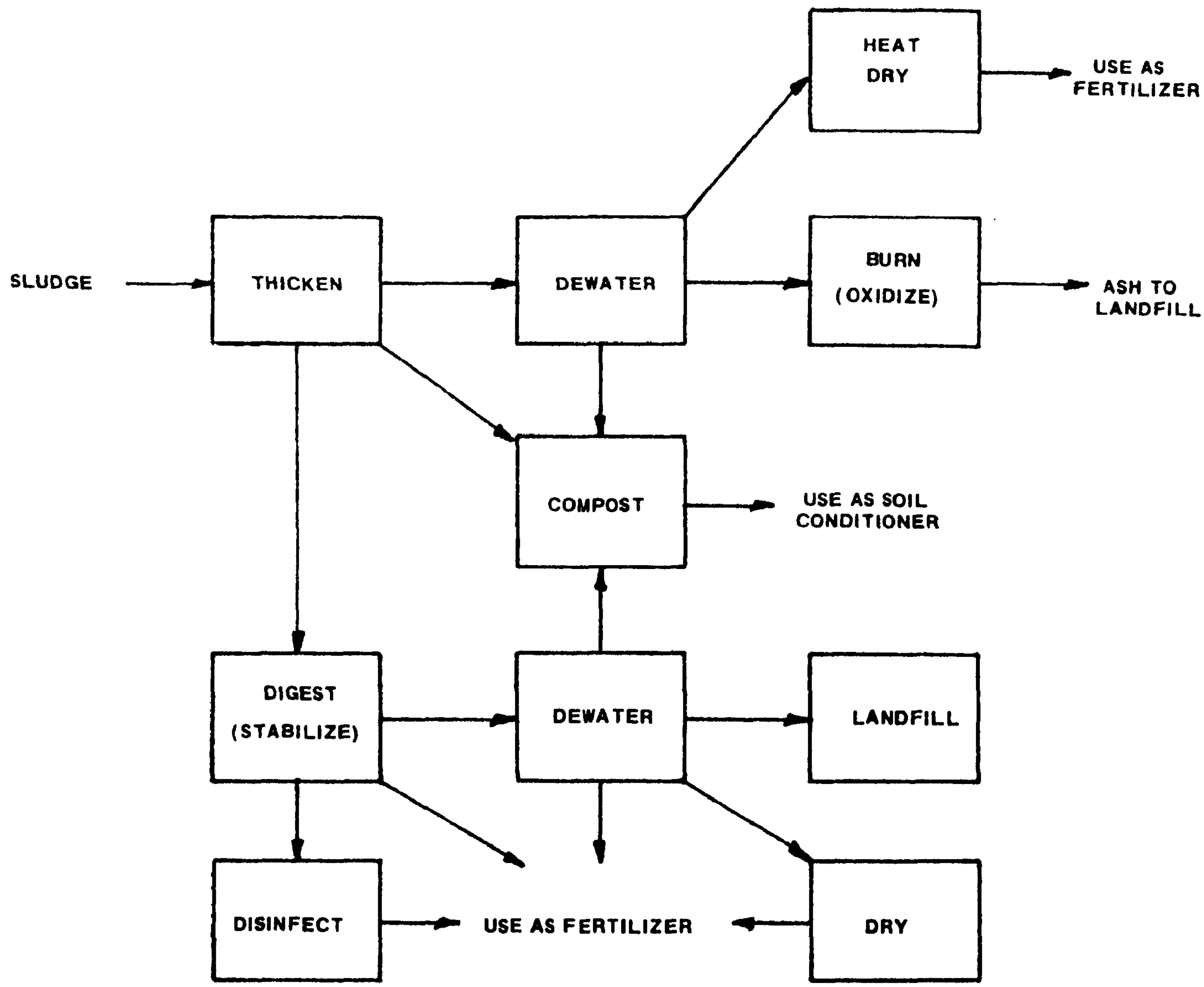


Figure 1

BASIC SLUDGE-HANDLING ALTERNATIVES

in the U.S. Subsequent portions of the paper discuss the available technology, costs, implementation considerations, and environmental impacts of the available alternatives.

SECTION IV

SLUDGE CHARACTERISTICS

The composition of sewage sludges from municipal systems varies widely from one locale to another depending on a variety of factors. The presence or absence of industrial wastes can have a profound effect on the quantity and quality of wastewater sludges. The chemical quality of the community's raw water supply will effect the chemical composition of the wastewater sludges. The presence or absence of stormwater in the system will also affect the sludge composition (i.e., by the amount of grit carried into the plant). Table 1 summarizes typical components of sewage sludges in 150 treatment plants in north central and eastern U.S.

Because the nature of sludges resulting from the treatment of municipal wastewaters varies so greatly from one locale to another, generalized statements about their nature are of limited value. However, some observations which are generally true follow.

Raw primary sludges almost universally settle, thicken and dewater with relative ease compared to secondary biological sludges due to their coarse, fibrous nature. Generally, at least 30% of the solids are larger than 30 mesh in size. These coarse particles permit rapid formation of a sludge cake with sufficient structural matrix to permit good solids capture and rapid dewatering. Contrary to some reports in the literature, anaerobic digestion of primary sludges frequently makes them somewhat more difficult to thicken and dewater. However, the dewatering results are still generally good at relatively low costs.

Activated sludges show much greater variation in dewatering characteristics than do primary sludges. These variations may even be substantial from day to day at the same plant. The sludges are much finer than primary sludges and are largely cellular organic material with a density very nearly the same as water. They are much more difficult to dewater than primary sludges.

The nature of sludges resulting from the chemical coagulation of sewage depends on the nature of the coagulant used. Generally, alum and iron coagulants produce gelatinous floc which is difficult to dewater. Lime coagulation produces a sludge which readily thickens and dewaters in most cases. Estimates of sludge quantities and characteristics from a variety of wastewater processes may be found in EPA's design manual for sludge treatment and disposal[4].

TABLE 1

MAJOR COMPONENTS OF SLUDGE[87]

Component	Sample Type	Sample Number	Range	Median	Mean
Organic C, %	Anaerobic	31	18- 39	26.8	27.6
	Aerobic	10	27- 37	29.5	31.7
	Other	60	6.5- 48	32.5	32.6
	All	101	6.5- 48	30.4	31.0
Total N, %	Anaerobic	85	0.5- 17.6	4.2	5.0
	Aerobic	38	0.5- 7.6	4.8	4.9
	Other	68	<0.1- 10.0	1.8	1.9
	All	191	<0.1- 17.6	3.3	3.9
NH_4-N, ppm	Anaerobic	67	120- 67,600	1,600	9,400
	Aerobic	33	30- 11,300	400	950
	Other	3	5- 12,500	80	4,200
	All	103	5- 67,600	920	6,540
NO_3-N, ppm	Anaerobic	35	2- 4,900	79	520
	Aerobic	8	7- 830	180	300
	Other	3	-- ---	---	780
	All	45	2- 4,900	140	490
Total P, %	Anaerobic	86	0.5- 14.3	3.0	3.3
	Aerobic	38	1.1- 5.5	2.7	2.9
	Other	65	<0.1- 3.3	1.0	1.3
	All	189	<0.1- 14.3	2.3	2.5
Total S, %	Anaerobic	19	0.8- 1.5	1.1	1.2
	Aerobic	9	0.6- 1.1	0.8	0.8
	Other	--	-- ---	---	---
	All	28	0.6- 1.5	1.1	1.1

TABLE 1 (CONT'D)

Component	Sample Type	Sample Number	Range	Median	Mean
			%		
K	Anaerobic	86	0.02- 2.64	0.30	0.52
	Aerobic	37	0.08- 1.10	0.38	0.46
	Other	69	0.02- 0.87	0.17	0.20
	All	192	0.02- 2.64	0.30	0.40
Na	Anaerobic	73	0.01- 2.19	0.73	0.70
	Aerobic	36	0.03- 3.07	0.77	1.11
	Other	67	0.01- 0.96	0.11	0.13
	All	176	0.01- 3.07	0.24	0.57
Ca	Anaerobic	87	1.9 - 20.0	4.9	5.8
	Aerobic	37	0.6 - 13.5	3.0	3.3
	Other	69	0.1 - 25.0	3.4	4.6
	All	193	0.1 - 25.0	3.9	4.9
Mg	Anaerobic	87	0.03- 1.92	0.48	0.58
	Aerobic	37	0.03- 1.10	0.41	0.52
	Other	65	0.03- 1.97	0.43	0.50
	All	189	0.03- 1.97	0.45	0.54
Ba	Anaerobic	27	<0.01- 0.90	0.05	0.08
	Aerobic	10	<0.01- 0.03	0.02	0.02
	Other	23	<0.01- 0.44	<0.01	0.04
	All	60	<0.01- 0.90	0.02	0.06
Fe	Anaerobic	96	0.1 - 15.3	1.2	1.6
	Aerobic	38	0.1 - 4.0	1.0	1.1
	Other	31	<0.1 - 4.2	0.1	0.8
	All	165	<0.1 - 15.3	1.1	1.3
Al	Anaerobic	73	0.1 - 13.5	0.5	1.7
	Aerobic	37	0.1 - 2.3	0.4	0.7
	Other	23	0.1 - 2.6	0.1	0.3
	All	133	0.1 - 13.5	0.4	1.2

TABLE 1 (CONT'D)

Component	Sample Type	Sample Number	Range	Median	Mean
			mg/kg		
Mn	Anaerobic	81	58- 7,100	280	400
	Aerobic	38	55- 1,120	340	420
	Other	24	18- 1,840	118	250
	All	143	18- 7,100	260	380
B	Anaerobic	62	12- 760	36	97
	Aerobic	29	17- 74	33	40
	Other	18	4- 700	16	69
	All	109	4- 760	33	77
As	Anaerobic	3	10- 230	116	119
	Aerobic	--	-- --	--	--
	Other	7	6- 18	9	11
	All	10	6- 230	10	43
Co	Anaerobic	4	3- 18	7.0	8.8
	Aerobic	--	-- --	--	--
	Other	9	1- 11	4.0	4.3
	All	13	1- 18	4.0	5.3
Mo	Anaerobic	9	24- 30	30	29
	Aerobic	3	30- 30	30	30
	Other	17	5- 39	30	27
	All	29	5- 39	30	28
Hg	Anaerobic	35	0.5-10,600	5	1,100
	Aerobic	20	1.0- 22	5	7
	Other	23	2.0- 5,300	3	810
	All	78	0.5-10,600	5	733

TABLE 1 (CONT'D)

Component	Sample Type	Sample Number	Range	Median	Mean
			mg/kg		
Pb	Anaerobic	98	58- 19,730	540	1,640
	Aerobic	57	13- 15,000	300	720
	Other	34	72- 12,400	620	1,630
	All	189	13- 19,700	500	1,360
Zn	Anaerobic	108	108- 27,800	1,890	3,380
	Aerobic	58	108- 14,900	1,800	2,170
	Other	42	101- 15,100	1,100	2,140
	All	208	101- 27,800	1,740	2,790
Cu	Anaerobic	108	85- 10,100	1,000	1,420
	Aerobic	58	85- 2,900	970	940
	Other	39	84- 10,400	390	1,020
	All	205	84- 10,400	850	1,210
Ni	Anaerobic	85	2- 3,520	85	400
	Aerobic	46	2- 1,700	31	150
	Other	34	15- 2,800	118	360
	All	165	2- 3,520	82	320
Cd	Anaerobic	98	3- 3,410	16	106
	Aerobic	57	5- 2,170	16	135
	Other	34	4- 520	14	70
	All	189	3- 3,410	16	110
Cr	Anaerobic	94	24- 28,850	1,350	2,070
	Aerobic	53	10- 13,600	260	1,270
	Other	33	22- 99,000	640	6,390
	All	180	10- 99,000	890	2,620

SECTION V

SLUDGE PROCESSING TECHNOLOGY

It is not the purpose of this section to provide detailed design guidance. Other readily available references (4-7) provide such information. This section will briefly describe available sludge processing technology. The discussion of each of the processes will center upon the aspects of major concern in developing regional plans such as results, costs, and implementation considerations. The costs and energy data used in this report were developed by Culp/Wesner/Culp under EPA Contract 68-03-2186 unless otherwise referenced. All cost and energy data presented in this report are based on detailed studies for a given set of conditions. The summary information presented herein will serve to put the various process in perspective but should not be used for a given project where conditions may vary significantly from those assumed for illustrative purposes. Technical conditions selected for illustrative costs are based on handling a mixture of primary and waste activated sludges - the most likely mixture to be encountered.

SLUDGE CONDITIONING

The purpose of sludge conditioning is to increase the rate and/or extent of dewatering achievable for a given sludge. A wide variety of physical and chemical techniques are used. The use of sludge conditioning prior to dewatering has become standard practice and their combined result permits the moisture content of sludges to be reduced form 95 to 98% to 60-75%.

Chemical Conditioning

The most frequently encountered conditioning practice in the U.S. today is the use of ferric chloride either alone or in combination with lime[(5)] although the use of polymers is rapidly gaining widespread acceptance. Although ferric chloride and lime are normally used in combination, it is not unusual for them to be applied individually. Lime alone is a fairly popular conditioner for raw primary sludge and ferric chloride alone has been used for conditioning activated sludges. Lime treatment to high pH value has the added advantage of providing a significant degree of disinfection of the sludge[(8)].

Organic polymeric coagulants, and coagulant aids that have been developed in the past 20 years, are rapidly gaining acceptance for sludge conditioning[(9)]. These polyelectrolytes are of three basic types:

1. Anionic (negative charge)- serve as coagulant aids complementing inorganic Al^{+++} and Fe^{+++} coagulants by increasing the rate of flocculation, size, and toughness of particles.

2. Cationic (positive charge)- serve as primary coagulants or in conjunction with inorganic coagulants.

3. Nonionic (equal amounts of positively and negatively charged groups in monomers)- serve as coagulant aids in a manner similar to that of both anionic and cationic polyelectrolytes.

The popularity of polymers is primarily due to their ease in handling, small storage space requirements, and their effectiveness. All of the inorganic coagulants are difficult to handle and their corrosive nature can cause maintenance problems in the storing, handling, and feeding systems in addition to the safety hazards inherent in their handling. Many plants in the U.S. have abandoned the use of inorganic coagulants in favor of polymers.

The facilities for chemical conditioning are relatively simple and consist of equipment to store the chemical(s), feed the chemical(s) at controlled dosages, and mix the chemical(s) with the sludge. The cost of chemical conditioning is primarily a function of the quantity of chemical required which is affected by factors such as:

1. Solids concentration.

2. Sludge particle size.

3. Proportion of volatile matter in sludge.

4. Reducing agents in sludge, i.e. H_2S.

5. Alkalinity.

The chemical requirements for any given sludge can be determined accurately only by tests on the specific sludge involved. Typical values are as follows[4,5]:

	$FeCl_3$ lbs/dry ton solids	Lime lbs CaO/dry ton solids	Polymer lbs/dry ton solids
Raw Primary + Activated Sludge	40-50	200	15-20
Digested Primary + Activated Sludge	80-100	160-370	30-40
Elutriated Primary + Activated Sludge	40-125	-	20-30

Chemical costs also vary widely from one locale to another. Typical chemical conditioning costs are $10-$25 per dry ton solids. The use of the inorganic chemical conditioning chemicals can increase the weight of sludge by 10-20%.

Energy consumed in the feeding and mixing of conditioning chemicals is negligible in terms of overall wastewater treatment plant energy consumption. However, the energy required to produce the chemicals consumed (secondary energy requirement) may be significant and may be summarized as follows:

	Fuel 10^6 BTU/ton	Electricity Kwh/lb
Ferric Chloride	10	0.5*
Lime (CaO)	5.5*	0.3
Polymer	3*	0.1

*Indicates principal type of energy used in production.

Elutriation

Elutriation is a washing operation which removes sludge constituents that interfere with thickening and dewatering processes. The process of elutriation was originally developed, and its use was justified, as an aid in the reduction (by one-fourth to one-half) of the inorganic chemical requirements for vacuum filtration of digested sludge. Digestion substantially reduces the organic fraction in sludge solids while increasing biochemical products such as ammonium bicarbonate which in turn significantly increase the flocculent demand exerted by a sludge.

Elutriation operations consist of "washing" the sludge solids with water or plant effluent in continuous or batch units. The washing operation flushes the bicarbonates from the sludge. The elutriate (or spent wash water) is recycled to the treatment plant and the sludge is pumped to the next solids handling process.

Elutriation may reduce the cost of chemical conditioning, but often causes a problem due to elutriate solids recycle. Recycling uncaptured elutriate solids can overload aeration facilities at activated sludge plants.

Estimates of the capital and operating cost of elutriation are typically less than $5 per ton of dry solids. Generally, savings in sludge conditioning chemicals will exceed this cost. However, any economic evaluation must also consider the added cost of properly handling the recycled elutriate. Energy requirements are 1,500-3,000 Kwh/ton of dry solids.

Many consulting engineers in the U.S. do not now consider elutriation when designing new waste treatment facilities. They believe the loss of solids in the elutriate is unavoidable and, therefore, the process is unsatisfactory even if high chemical costs for mechanical dewatering are required as a substitute.

Heat Treatment

There are two basic types of high temperature-high pressure treatment of sludges. One - "wet air oxidation" - involves the flameless oxidation of sludges at 450-550°F at pressures of about 1200 psig. Wet air oxidation is discussed in the subsequent section on sludge reduction processes. The other type - "heat treatment" is carried out at lower temperatures and pressures (350-400°F at 150-300 psig) to improve the dewaterability of sludges and is the subject of this section.

When colloidal gel systems are heated, thermal activity causes water to escape from the structure. It is the goal of heat treatment systems to release bound water form the sewage sludge to improve the dewatering and thickening characteristics of the sludge. Unfortunately, the physical effect of heat treatment also ruptures the cell walls of biological sludges, releasing bound organic colloidal material, solubilizes previously insoluble organic material, and creates fine particulate debris. This solubilization process means that a principal result of heat treatment is the conversion of suspended solids to dissolved or dispersed solids, facilitating dewatering, but simultaneously creating a separate problem of recycling of highly polluted liquid from the dewatering process to the wastewater treatment plant. This recycling must be recognized when assessing the feasibility of heat treatment.

Heat treatment is a conditioning technique which has had increasing use by consulting engineers although its use is still limited when compared to the large number of plants using other techniques for sludge conditioning. Several operating heat treatment plants have had significant operational problems from (1) the increased loadings of BOD, COD, nitrogen, phosphorus, and suspended solids on the secondary plant and (2) the refractory nature of a portion of the recycled load which will pass through the secondary plant as COD and can cause taste and odor problems in downstream water plants. The COD refractory to the biological processes has also been found difficult to remove by advanced wastewater treatment processes such as activated carbon adsorption. The refractory nature of the recycled organics may limit the applicability of this conditioning process in areas where downstream water uses dictate very low effluent COD values. Odor problems in the vicinity of some heat treatment facilities have been a problem.

An advantage of the heat treatment of sludges is that it produces a more readily dewaterable sludge than chemical conditioning. Dewatered sludge solids of 30-40% (as opposed to 15-20% with chemical conditioning) have been achieved with heat treatment at relatively high loading rates on the dewatering equipment (2-3 times the rates with chemical conditioning). The process also provides effective disinfection of the sludge.

A typical heat treatment process (Zimpro LPO) is shown in Figure 2. Sludge is ground and pumped to a pressure of about 300 psi. Compressed air is introduced into the sludge and the mixture is brought to an operating temperature of above 350°F by heat exchange and direct steam injection and flows to the reactor. The heated, conditioned sludge is cooled

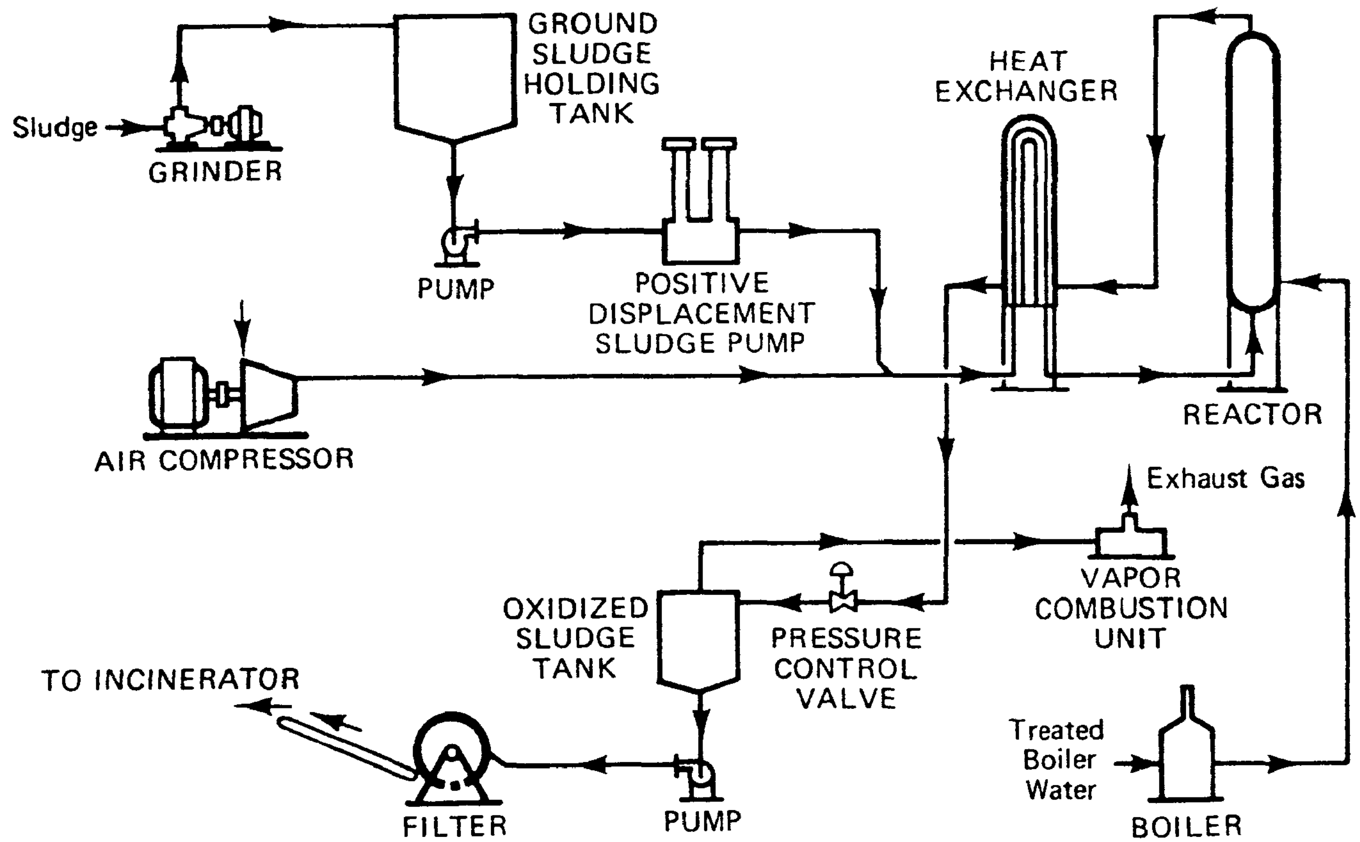


FIGURE 2. Zimpro LPO system.

by heat exchange with the incoming sludge. The treated sludge is separated by settling before the dewatering step. Gases released at the separation step are passed through a catalytic afterburner at 650-750°F. The system is more mechanically complex than many unit processes in municipal wastewater treatment plants and some installations have encountered significant maintenance problems.

An extensive analysis of the costs of heat treatment of sludges under EPA Contract 68-03-2186 was summarized in a recent paper[10]. Analyses of costs are complicated by the fact that an accurate estimate must reflect the indirect costs associated with treatment of the recycled polluted liquors to the treatment plant. For the typical conditions described in the paper[10], the illustrative costs presented in Table 2 were developed. It is apparent that heat treatment costs become very high at smaller capacities. In evaluating costs, the total system (conditioning, dewatering, disposal) costs must be considered. The fact that heat treatment produces a more readily dewaterable sludge produces economies in downstream dewatering processes. It may produce a sludge dry enough to burn without auxiliary fuel, providing some downstream savings.

Electricity requirements are 100-150 Kwh/ton of dry solids with fuel requirements of about 3×10^6 BTU/ton of dry solids (for primary + waste activated sludge at 4.5% solids).

Freezing

A number of people have observed that sludge frozen and later thawed in sand drying beds or lagoons had good dewatering and fertilizer or soil-conditioning characteristics. Thawed sludge was stable and dewatered rapidly if provisions were made for water drainage[11]. These observations encouraged researchers, particularly in Great Britain, to evaluate artificial freezing of sludge as a means to promote rapid dewatering.

The City of Milwaukee, Wisconsin has studied the process[12,13] for application to activated sludge. These studies found that vacuum filter rates of 55 psf/hour were achievable; the filtrate and filter cake quality were equivalent or better than that produced from conventional vacuum filter operation; freeze conditioned sludge could be dewatered by a wire screen cloth (40-80 mesh) by gravity draining; and that freezing rate was an important variable.

Early engineering studies at Milwaukee revealed that equipment costs and space requirements would be substantially higher than for chemical conditioning techniques currently employed, and that space requirement for freeze-conditioning would be 65 to 130 times that required for the conventional chemical dewatering system. Equipment costs for the freeze-conditioning system were estimated at 7 to 10 times those for the chemical conditioning process. The estimated annual operating costs for freeze-conditioning process was 3 to 4 times that of the chemical conditioning approach.

Coupled with the high capital cost, very high operating cost has been the major reason why freezing has not been adopted as a conditioning

TABLE 2[10]

SUMMARY OF DIRECT AND INDIRECT COST FOR
THERMAL TREATMENT

Sludge[1]	Construction Cost[2,3,4]			O & M Cost			
Ton/Day	Direct	Indirect	Total	Direct	Indirect	Total	Total Cost
1	97.53	4.11	101.64	150.14	4.93	155.07	256.71
5	30.79	3.18	33.97	46.46	3.67	50.13	84.10
10	21.45	2.93	24.38	32.52	3.50	36.02	60.40
50	12.20	1.83	14.03	19.10	2.99	22.09	36.12
100	10.96	1.98	12.94	16.58	2.87	19.45	32.39

(1) Basis

a) 1.1 tons solids per mgd-includes recycle

b) 4 gpm to thermal treatment per mgd @ 4½% solids

c) 8000 hrs/yr operating time

(2) Ammortized 20 years-7%

(3) All costs in dollars/ton

(4) Not including odor control

technique for wastewater sludge.

Hydrolysis with Sulfur Dioxide

This process consists of heating activated sludge in the presence of water and small amounts of sulfur dioxide to improve its dewatering characteristics. This treatment increases soluble solids and produces a filtrate which can be concentrated to produce a molasses-type syrup which could be of value as an animal feed[14-16].

A small scale study has been made to preliminarily evaluate the feasibility of the hydrolysis process applied to sewage sludge. It was found that the filtration rate of activated sludge was increased by a factor of six when SO_2 was added to the activated sludge before heat treatment while heat treatment alone increased the rate by a factor of only three. The amount of moisture retained in the filter cake was also reduced by the SO_2 treatment. It was found that heat treatment alone increases the soluble solids content of activated sludge by about 90% and that an additional 20% was obtained by the addition of SO_2 (0.5% sulfurous acid, 140°C for one hour). Evaporation of the filtrate to a syrup with 60% solids produced a molasses which was 82% organic.

Preliminary cost estimates indicated that the sale of the molasses resulting from this process could recover about 20% of the cost of the hydrolysis treatment. The SO_2 hydrolysis process has not yet been tried on sewage sludges on a plant-scale or continuous basis. Thus, the economics of the process and the marketability of the resulting molasses are yet to be demonstrated.

Radiation Treatment

Radiation of sludges produces charged and oxidizing species which affect colloidal systems and may improve the thickening and dewatering characteristics of the sludges[17]. A limited amount of data are available on the feasibility of using radiation treatment for sludge conditioning[17-20]. A preliminary analysis of the economic feasibility indicated that if a dosage of 10^5 rads would enable a doubling of the vacuum filtration rate, that the costs of radiation treatment would be of the same order of magnitude as the potential savings.

A study of the effects of gamma irradiation on the settleability and filterability of digested activated sludge indicated that a dose of 5×10^5 rad showed essentially no effect on the settling properties of the sludge but, in combination with ferric chloride conditioning to approximately one-third of the optimum conditioning dosage, was able to effect about a three-fold increase in the dewaterability. The filterability of undigested activated sludge was not increased by the same treatment.

Another study[19] found that irradiation produced a marked effect on the filterability of sludge but that this effect saturated at a dose of approximately 10^5 rads at a level of specific resistance too high to permit the sludges to be filtered at a useful rate on a rotary vacuum filter. The range of specific resistance needed for effective vacuum filtration could not be reached with the use of ionizing radiation alone.

The use of radiation for sludge conditioning is not currently practiced in the U.S. and it does not appear likely that it will be in the near future.

The disinfection of sewage sludge by bombardment with an electron beam is being tried on a large scale at the Deer Island sewage treatment plant in Boston Harbor. The facility uses a 50-kilowatt electron generator. A beam of electrons sweeps back and forth across a four-ft. wide, two-millimeter deep stream of sludge that is passing over a metal drum at the rate of more than six ft. per second. In one hundredth of a second, the water receives a radiation dose of 4000,000 rads.

SLUDGE THICKENING

The purpose of sludge thickening is to reduce the sludge volume to be stabilized, dewatered, or disposed of. Figure 3 illustrates the impact that thickening can have on sludge volume. Thickening a 1% sludge to 6% solids reduces the volume of sludge to be handled by a factor of over 5. This reduction can provide significant savings in the cost of dewatering, digestion, or other downstream facilities. There are three commonly used methods for sludge thickening: gravity, flotation, and centrifugation.

Gravity Thickening

Thickening by gravity is the most common concentration process in use at wastewater treatment plants. It is simple and inexpensive. Gravity thickening is essentially a sedimentation process similar to that which occurs in all settling tanks. But, in comparison with the initial waste clarification stage, the thickening action is relatively slow. The theoretical aspects of gravity thickening have been the subject of many studies and are well summarized in a few recent papers[21-25].

Figure 4 illustrates a typical, circular gravity thickener. The units have a typical side water depth of 10 feet. Loading rates are expressed in terms of pounds of dry solids in the sludge applied to the thickener surface area per day (lbs/day/sf). Table 3 summarizes typical results achieved with gravity thickening.

The degree to which waste sludges can be thickened depends on many factors; among the most important are the type of sludge being thickened and its volatile solids concentration. Bulky biological sludge, particularly that from the activated sludge process, will not concentrate to the same degree as raw primary sludge. Activated sludges, if thickened separately, are usually thickened by the flotation process. The degree of biological treatment and the ratio of primary to secondary (biological) sludge will affect the ultimate solids concentration obtained by gravity thickening. Hydraulic and surface loading rates are also of importance. Current practice calls for the use of overflow rates of 400-800 gpd/sq.ft. Excessively low flow rates can lead to odor problems. If the sludge flow

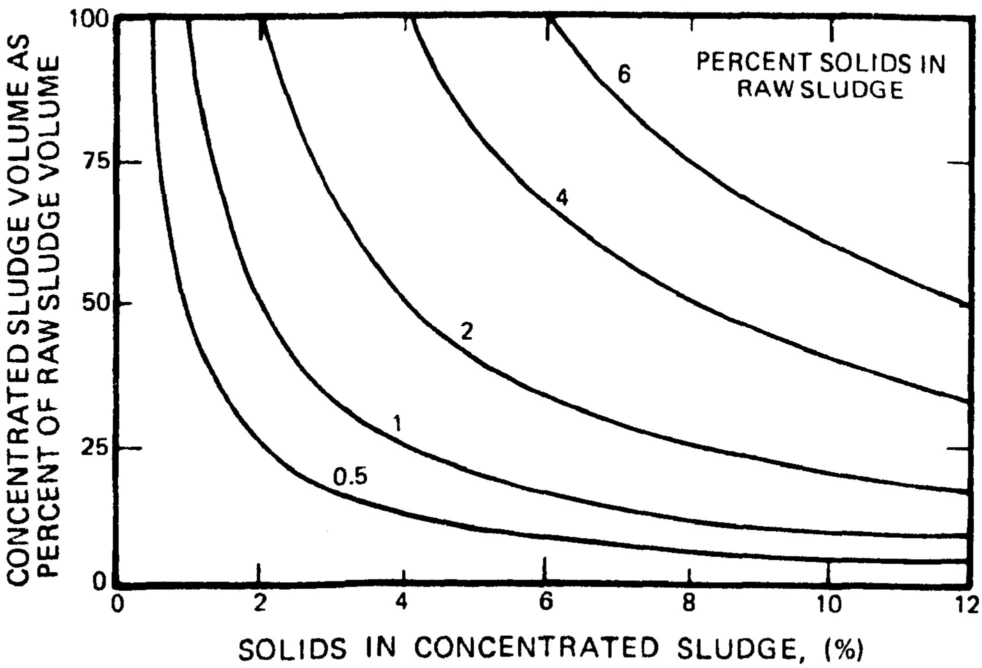


FIGURE 3 Effect of increasing sludge solids on the final sludge volume (4)

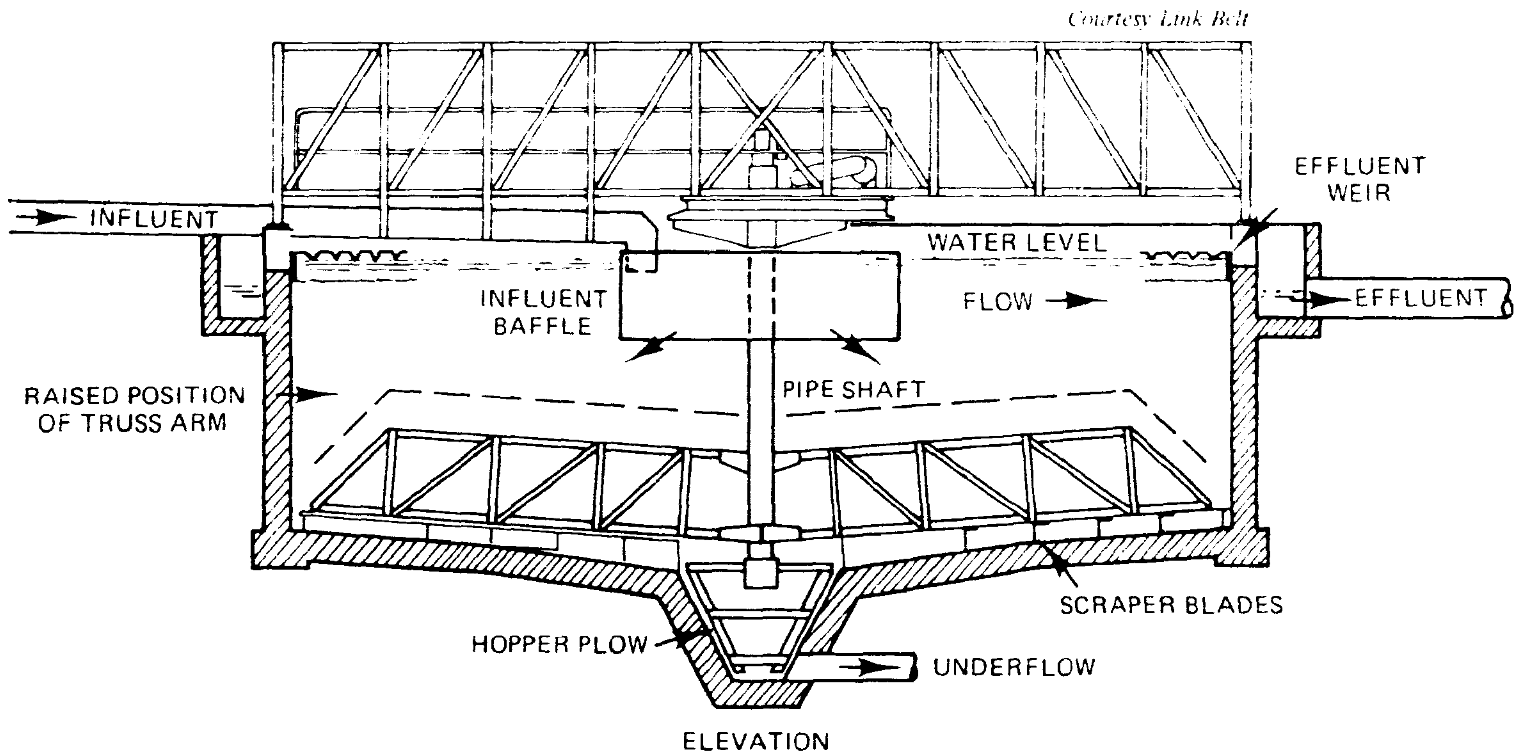


FIGURE 4 Gravity thickener

TABLE 3

TYPICAL RESULTS -

GRAVITY THICKENING

Sludge Type	Feed Solids Concentration (Percent)	Typical Loading Rate (lb/sqft/day)	Thickened Sludge Concentration (Percent)
Primary	5.0	20-30	8.0-10
Trickling Filter	1.0	8-10	7-9
Primary + $FeCl_3$	2.0	6	4.0
Primary + Low Lime	5.0	20	7.0
Primary + High Lime	7.5	25	12.0
Primary + WAS*	2.0	6-10	4.0
WAS	1.0	5-6	2-3
Primary + (WAS + $FeCl_3$)	1.5	6	3.0
(Primary + $FeCl_3$) + WAS	1.8	6	3.6
Digested Primary	8.0	25	12.0
Digested Primary + WAS	4.0	15	8.0
Digested Primary + (WAS + $FeCl_3$)	4.0	15	6.0
Tertiary, 2 stage high lime	4.5	60	15.0
Tertiary, low lime	3.0	60	12.0

*WAS = Waste Activated Sludge

to the thickener is far below the design rate, pumping of secondary effluent to the thickener may be practiced to minimize odors.

There is some evidence[26] that activated sludges from systems using pure oxygen gravity thicken more readily than those sludges from conventional air systems, at that, concentrations of 4-6% may be achieved at rates of 10-20 lbs/day/sf.

The quality of the overhead liquid removed from the sludge solids is important in any thickening operation because this liquid is usually returned to the treatment processes. Generally, the overhead quality is similar to that of raw sewage, 150 to 300 mg/l suspended solids and a BOD of about 200 mg/l. A well-operated thickener should have a minimum of anaerobic decomposition and a solids capture exceeding 90 percent. Thus, the overflow returned to the treatment process should not present an operational problem.

Table 4 summarizes the estimated cost of gravity thickening based on a loading rate of 20 lbs/day/sf. The electrical consumption of the process is low - on the order of 1-1.5 kwh/ton of solids.

Flotation Thickening

Flotation thickening units are becoming increasingly popular for sewage treatment plants in the U.S., especially for handling waste activated sludges where they have the advantage over gravity thickening tanks of offering higher solids concentrations and lower initial cost for the equipment. The objective of flotation-thickening is to attach a minute air bubble to suspended solids and cause the solids to separate from the water in an upward direction due to the fact that the solid particulates have a specific gravity lower than water when the bubble is attached.

Figure 5 illustrates the basic considerations involved in the process. A portion of the unit effluent, or plant effluent, is pumped to a retention tank (a pressurization tank) at 60-70 psig. Air is fed into the pump discharge line at a controlled rate and mixed by the action of an educator driven by the reaeration pump. The flow through the recycle system is metered and controlled by a valve located immediately before the mixing with the sludge feed. The recycle flow and sludge feed are mixed in a chamber at the unit inlet. If flotation aids (such as polymers) are employed, introduction is normally in this mixing chamber. The sludge particles are floated to the sludge blanket and the clarified effluent is discharged under a baffle and over an adjustable weir. The thickened sludge is removed by a variable speed skimming mechanism. In practice bottom sludge collectors are also furnished for removal of any settled sludge or grit that may accumulate. Sludge thickening occurs in the sludge blanket, which is normally 8" to 24" thick. The buoyant sludge and air bubbles force the surface of the blanket above the water level, inducing drainage of water from the sludge particles.

Similar to gravity thickening, the type of quality of sludge to be floated affects the unit performance. Flotation thickening is, as stated

TABLE 4

GRAVITY THICKENING COSTS

Item	Tons Per Day of Dry Solids			
	10	25	50	100
Construction Cost	$120,000	$160,000	$320,000	$540,000
Engr., Legal, Adm., & Interest During Construction (19%)	22,800	30,400	60,800	102,600
Total Capital Cost	$142,800	$190,400	$380,800	$642,600
O & M Labor @ $10/Hr.	3,600	4,400	6,000	10,000
Power @ $0.025/Kwh	100	300	500	800
Maintenance Materials	400	700	1,300	2,200
Annual O & M Costs	4,100	5,400	7,800	13,000
Annual Capital Cost (x .0944)	13,500	18,000	36,000	60,700
Total Annual Cost	$ 17,600	$ 23,400	$ 43,800	$ 73,700
Cost per ton of dry solids	$4.80	$2.60	$2.40	$2.00

Assumption: 20 lbs/day/sf loading rate.

Courtesy Komline-Sanderson

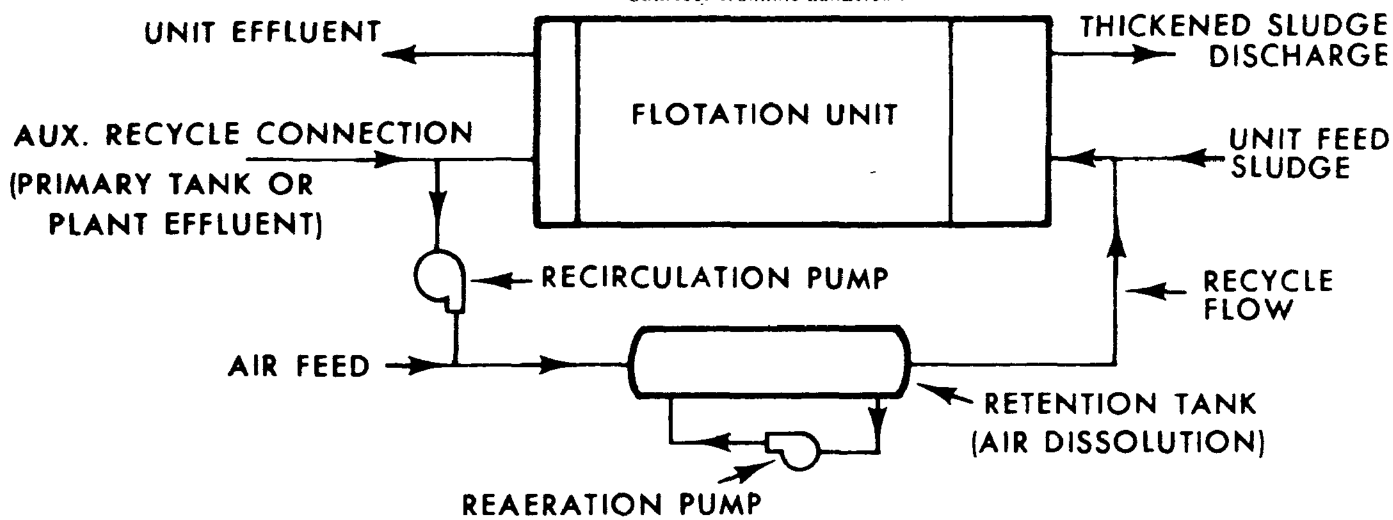


FIGURE 5 Dissolved air flotation system.

before, most applicable to activated sludges but higher float concentrations can be achieved by combining primary with activated sludge. However, equal or greater concentrations may be achieved by combining sludges in gravity thickening units. A high Sludge Volume Index (SVI), representing a bulky sludge, results in poor thickener performance. Table 5 presents typical results from flotation thickening.

Many different chemicals have been used in various air flotation systems. The overall effect is to increase the allowable solids loadings, increase the percentage of floated solids, and increase the clarity of the effluent. Cationic polyelectrolytes have been the most successful chemical used in sewage sludge thickening[27-30] with dosages of 8-12 lbs/ton reported as typical. There is some evidence[26] that activated sludges from pure oxygen systems are more amenable to flotation thickening than activated sludges from conventional air systems. Pilot tests at Louisville, Kentucky indicate that with polymer doses of only about 3 pounds per ton of dry solids, an influent solids of 1.7-2% was increased to 6-7% solids at loading rates of 6-10 psf/hour with 200% recycle and 97-99% solids recovery. Similar results have been observed on a plant scale at the Westgate plant in Fairfax County, Virginia (6-8% solids with 3 pounds of polymer per ton)[31].

Table 6 presents typical costs for flotation thickening at a loading rate of 40 lbs/day/sf <u>not</u> including any chemical feed costs. Polymer costs could add from $1-$15/ton of solids. Electrical consumption is about 100 kwh/ton of solids.

Centrifugal Thickening

Although centrifuges have been used widely for dewatering (See page V-23), they have had limited use for thickening because of relatively high cost. They have been used for thickening of WAS where space limitations or sludge characteristics make other methods unsuitable[4]. WAS concentrations of 5-8% have been typically produced by centrifugal thickening.

SLUDGE DEWATERING

Drying Beds

The most widely used dewatering method in the United States is drying of the sludge on open or covered sandbeds. Over 6,000 wastewater treatment plants use this method[4]. They are especially popular in small plants. Sandbeds possess the advantage of needing little operator skill. Air drying is normally restricted to well digested sludge, because raw sludge is odorous, attracts insects, and does not dry satisfactorily when applied at reasonable depths. Oil and grease discharged with raw sludge clog sandbed pores and thereby seriously retard drainage. The design and use of drying beds are affected by many parameters. They include weather conditions, sludge characteristics, land values and proximity of residences, and use of sludge conditioning aids. Climatic conditions are most important. Factors such as the amount and rate of precipitation, percentage of sunshine,

TABLE 5

TYPICAL RESULTS

FLOTATION THICKENING

Sludge Type	Feed Solids Concentration (Percent)	Typical Loading Rate Without Polymer (lb/sqft/day)	Typical Loading Rate With Polymer (lb/sqft/day)	Float Solids Concentration (Percent)
Primary + WAS	2.0	20	60	5.5
Primary + (WAS + $FeCl_3$)	1.5	15	45	3.5
(Primary + $FeCl_3$) + WAS	1.8	15	45	4.0
WAS	1.0	10	30	3.0
WAS + $FeCl_3$	1.0	10	30	2.5
Digested Primary + WAS	4.0	20	60	10.0
Digested Primary + (WAS + $FeCl_3$)	4.0	15	45	8.0
Tertiary, Alum	1.0	8	24	2.0

TABLE 6

FLOTATION THICKENING COSTS

Item	Tons Per Day of Dry Solids 10	25	50	100
Construction Cost	$200,000	$290,000	$380,000	$500,000
Engr., Legal, Adm., & Interest During Construction (19%)	38,000	55,100	72,200	95,000
Total Capital Cost	$238,000	$345,100	$452,200	$595,000
O & M Labor @ $8/Hr.	9,600	22,400	44,800	89,600
Power at $0.025/Kwh	10,000	20,000	40,000	75,000
Maintenance Materials	200	300	500	1,000
Annual O & M Costs	19,800	42,700	85,300	165,600
Annual Capital Costs (x .0944)	22,500	32,600	42,700	56,200
Total Annual Cost	$ 42,300	$ 75,300	$128,000	$221,800
Cost per ton of dry solids	$11.60	$8.30	$7.00	$6.10

Assumption: 40 lbs/day/sf loading rate.

air temperature, relative humidity, and wind velocity determine the effectiveness of air drying. It is important that wastewater sludge be well digested for optimum drying. In well digested sludge, entrained gases tend to float the sludge solids and leave a layer of relatively clear liquid, which can readily drain through the sand. Typical design criteria are:

Type of Digested Sludge	Area (sq ft/capita)	Sludge Loading Dry Solids (lb/sq ft/yr)
Primary	1.0	27.5
Primary and standard trickling filter	1.6	22.0
Primary and activated	3.0	15.0
Chemically precipitated	2.0	22.0

Sandbeds can be enclosed by glass. Glass enclosures protect the drying sludge from rain, control odors and insects, reduce the drying periods during cold weather, and can improve the appearance of a waste treatment plant. Experience has shown that only 67 to 75 percent of area required for an open bed is needed for an enclosed bed. Good ventilation is important to control humidity and optimize the evaporation rate. As expected, evaporation occurs rapidly in warm, dry weather. Adaptation of mechanical sludge removal equipment to enclosured beds is more difficult than to open drying beds.

Mechanical removal of sludge from drying beds has been practiced for many years at some large treatment plants, but now it is receiving more attention as the need to minimize problems with labor costs. Mechanical devices can remove sludges of 20 to 30 percent solids while cakes of 30 to 40 percent are generally required for hand removal. Small utility tractors with front end loaders are often used for mechanical removal.

Drying times typically range from 4-12 weeks, depending upon the weather. Especially adverse weather can result in drying times as long as 6 months[11].

A major disadvantage in the larger plants likely to be involved in regional systems is the space required. For a 10 mgd activated sludge plant, about 11 acres of drying beds would be required for the primary and WAS at a loading rate of 15 lbs/yr/sf. The space requirements plus dependency on uncontrollable weather factors are severe restrictions on the use of drying beds in large, regional plants. The limited cost data available[32] for large drying beds (adequate for 10-25 mgd activated sludge plants) indicate total costs would be $70-$90/ton of dry solids.

Vacuum Filtration

A vacuum filter basically consists of a cylindrical drum (see Figure 6) which rotates partially submerged in a vat of sludge. The filter drum is divided into compartments by partitions or seal strips. A vacuum is applied between the drum deck and filter medium causing filtrate to be extracted and filter cake to be retained on the medium during the pickup and cake drying cycle. In the drum filter shown in Figure 6, the cake of dewatered sludge is removed by a fixed scraper blade. There are alternative designs which use other methods for sludge removal.

The performance of vacuum filters may be measured by various criteria such as the yield, the efficiency of solids removal and the cake characteristics. Each of these criteria is of importance, but one or the other may be particularly significant in a given plant. Typical results are shown in Table 7.

Yield is the most common measure of filter performance. The yield expresses the filter output and is expressed in terms of pounds of dry total solids in the cake discharged from the filter, per square foot of effective filter area, per hour.

The second measure of filter performance is the efficiency of solids removal. Basically, the vacuum filter is a device used for separating solid matter from liquid, and the actual efficiency of the process is the percentage of feed solids recovered in the filter cake. Solids removals on vacuum filters range from about 85 percent for coarse mesh media to 99 percent with close weave, long nap media. The re-cycled filtrate solids impose a load on the plant treatment units, and should normally be kept to a practical minimum. However, it may be necessary to reduce the filter efficiency in order to deliver more filter output and thus keep up with sludge production.

The filter cake quality is another measure of filter performance, depending upon cake moisture and heat value. Cake solids content varies from 20 to 40 percent by weight, depending upon the type of sludge handled and the filter cycle time and submergence. Delivery of a very dry cake does not necessarily indicate good filter performance. Cake moisture should be adjusted to the method of final disposal, and it is inefficient to dry the cake more than is required. When incineration is practiced, a raw sludge cake having a fairly high moisture content can be burned without auxiliary fuel because of the higher volatile content, while a digested sludge cake will have to be dryer to burn successfully without make-up heat. One approach to improving the filtration and incineration characteristics of primary - WAS mixtures is to feed powdered coal as a conditioning agent prior to the dewatering step[34]. It was found that a coal dose of about 0.3 lbs/lb dry sludge solids produced a sludge cake which permitted autogenous combustion with no effect on filter yield.

The effect of heat treatment prior to vacuum filtration on various municipal sludges is to make all types dewaterable to approximately the

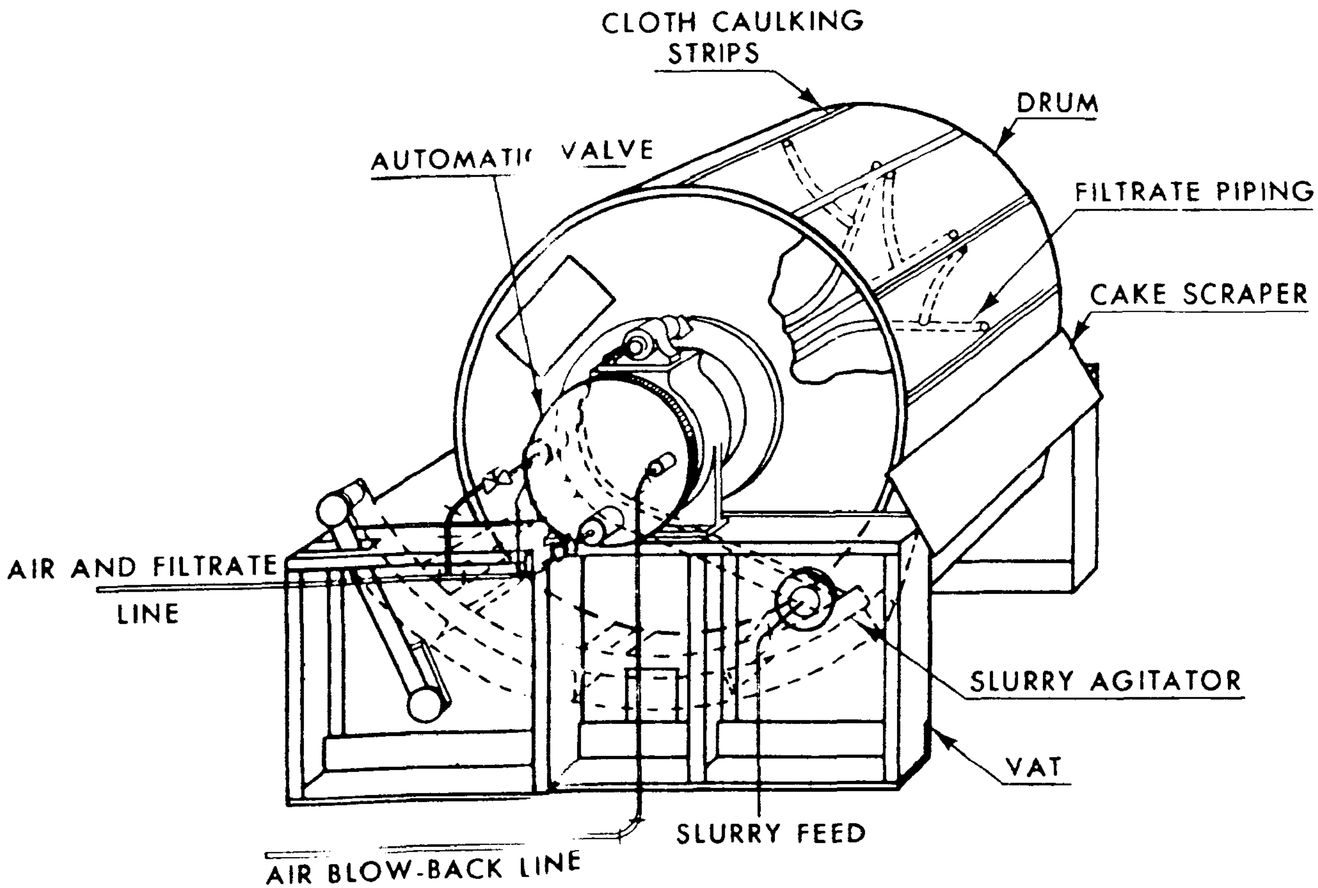


FIGURE 6 Cutaway view of a rotary drum vacuum filter.

TABLE 7

TYPICAL RESULTS
VACUUM FILTRATION

Sludge Type	Design Assumptions	Percent Solids To VF	Typical Loading Rates, (psf/hr)	Percent Solids VF Cake
Primary	Thickened to 10% solids polymer conditioned	10	8-10	25-38
Primary + $FeCl_3$	85 mg/l $FeCl_3$ dose Lime conditioning Thickening to 2.5% solids	2.5	1.0-2.0	15.20
Primary + Low Lime	300 mg/l lime dose Polymer conditioned Thickened to 15% solids	15	6	32-35
Primary + High Lime	600 mg/l lime dose Polymer conditioned Thickened to 15% solids	15	10	28-32
Primary + WAS	Thickened to 8% solids Polymer conditioned	8	4-5	16-25
Primary + (WAS + $FeCl_3$)	Thickened to 8% solids $FeCl_3$ & lime conditioned	8	3	20
(Primary + $FeCl_3$) + WAS	Thickened primary sludge to 2.5% Flotation thickened WAS to 5% Dewater blended sludges	3.5	1.5	15-20
Waste Activated Sludge (WAS)	Thickened to 5% solids Polymer conditioned	5	2.5-3.5	15
WAS + $FeCl_3$	Thickened to 5% solids Lime + $FeCl_3$ conditioned	5	1.5-2.0	15
Digested Primary	Thickened to 8-10% solids Polymer conditioned	8-10	7-8	25-38
Digested Primary + WAS	Thickened to 6-8% solids Polymer conditioned	6-8	3.5-6	14-22
Digested Primary + (WAS + $FeCl_3$)	Thickened to 6-8% solids $FeCl_3$ + lime conditoned	6-8	2.5-3	16-18
Tertiary Alum	Diatomaceous earth precoat	0.6-0.8	0.4	15-20

same degree[33]. Heat treatment provides a sludge that is readily dewaterable from primary or secondary sludges. Raw primary sludges have been dewatered at rates as high as 40 psf/hr and waste activated sludges at 7 psf/hr. Mixtures of raw primary and secondary sludges subjected to heat treatment should produce yields well over 10 psf/hr.

Illustrative costs based on an average loading rate of 4 psf/hr are shown in Table 8. Typical electrical consumption is 40-60 kwh/ton of solids.

Centrifugation

There are many types of centrifugal equipment available, for a variety of specialized applications in industry[35,36]. However, the solid bowl centrifuge is the most widely used type for dewatering of sewage sludge. The solid bowl-conveyor sludge dewatering centrifuge assembly (Figure 7) consists of a rotating unit comprising a bowl and conveyor. The solid cylindrical-conical bowl, or shell, is supported between two sets of bearings and includes a conical section at one end to form a dewatering beach or drainage deck over which the helical conveyor screw pushes the sludge solids to outlet ports and then to a sludge cake discharge hopper. Sludge slurry enters the rotating bowl through a stationary feed pipe extending into the hollow shaft of the rotating screw conveyor and is distributed through ports into a pool within the rotating bowl.

As the liquid sludge flows through the cylindrical section toward the overflow devices, progressively finer solids are settled centrifugally to the rotating bowl wall. The helical rotating conveyor pushes the solids to the conical section where the solids are forced out of the water, and free water drains from the solids back into the pool.

There are several variables which affect the performance of solid bowl centrifuges. Bowl speed is one of the prime variables since centrifugal force speeds up the separation of solids from liquids. At any given pool depth, an increase in bowl speed provides more gravity-settling force, providing greater clarification. Typical G values for a solid bowl machine for many years were about 3,000. In recent years, units which operate at G=700 have been developed. These "low" speed units provide comparable results at lower power consumption.

The introduction of polymers, has increased the range of materials that can be dewatered satisfactorily by centrifuges. The degree of solids recovery can be regulated over rather wide ranges depending on the amount of coagulating chemical used. Wetter sludge cake usually results from the use of flocculation aids because of the increased capture of fines.

Table 9 presents data on typical results with solid bowl centrifugation. Heat treated sludges will dewater to 35-45% solids with no polymer required for 85% capture. Recovery of 92-99% of the solids from heat treatment (primary) sludges have been reported[33] with polymer dosage

TABLE 8

ESTIMATED COSTS FOR DEWATERING BY VACUUM FILTER

Item	Tons Per Day of Dry Solids			
	10	25	50	100
Construction Cost	$270,000	$470,000	$780,000	$1,400,000
Engr., Legal, Adm., & Interest During Construction (19%)	51,300	89,300	148,200	266,000
Total Capital Cost	$321,300	$559,300	$928,200	$1,666,000
Labor, Operations at $10/Hr.	47,000	90,000	160,000	270,000
Labor, Maintenance at $10/Hr.	8,000	17,000	28,000	51,000
Maintenance Materials, Chemical	46,000	100,000	180,000	310,000
Maintenance Materials, Other	24,000	45,000	72,000	120,000
Annual O & M Costs	$125,000	$252,000	$440,000	$ 751,000
Annual Capital Costs (x .0944)	30,300	52,800	37,600	157,300
Total Annual Cost	$155,300	$304,800	$477,600	$ 908,300
Cost per ton of dry solids	$42.60	$33.40	$26.20	$24.90

Assumptions: Primary + WAS
4 lbs/hr/sf loading rate

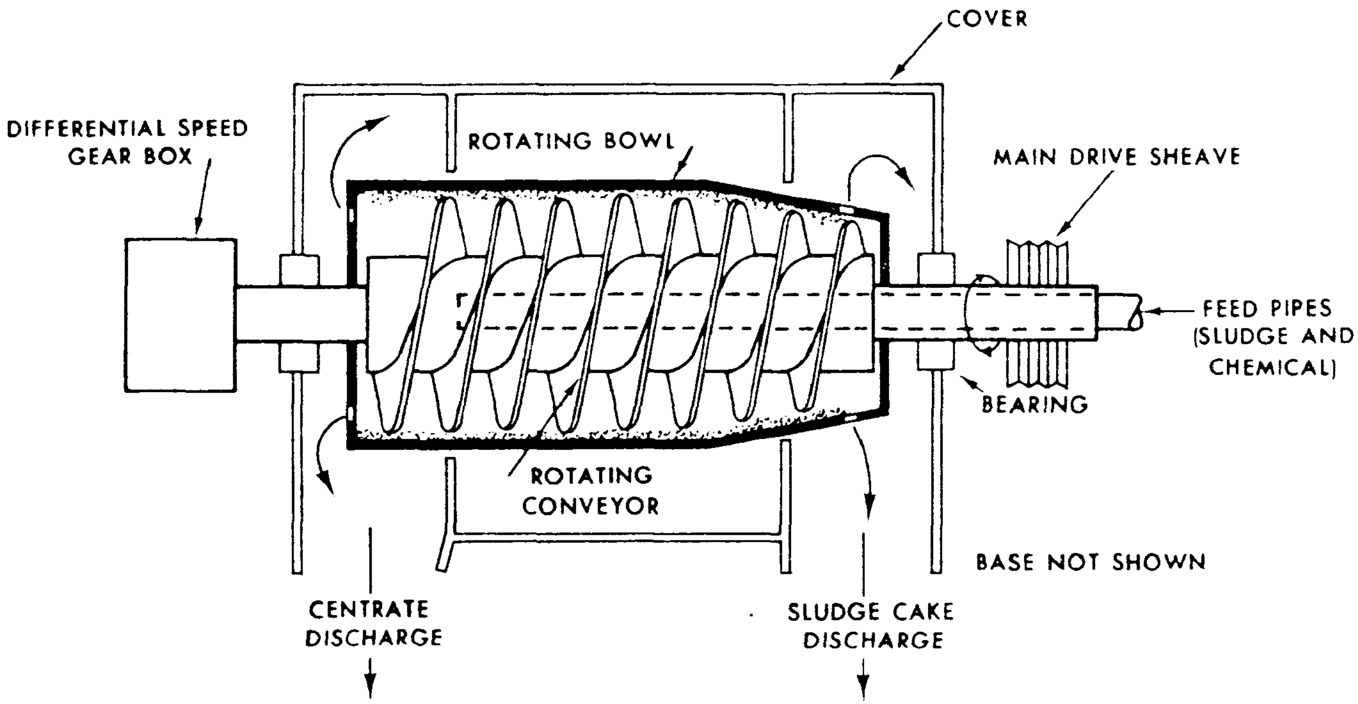


FIGURE 7 Continuous countercurrent solid bowl conveyor discharge centrifuge.

TABLE 9

TYPICAL SOLID BOWL CENTRIFUGE PERFORMANCE

Wastewater Sludge Type	Sludge Cake Characteristics		
	Solids (%)	Solids Recovery (%)	Polymer Addition
Raw or digested primary	28-35	70-90	no
Raw or digested primary, plus trickling filter humus	20-30	80-95	yes(5-15 lbs/ton)
		60-75	no
Raw or digested primary, plus activated sludge	15-30	80-95	yes(5-20 lbs/ton)
		50-65	no
Activated Sludge	8-9	80-85	5-10 lbs/ton
Oxygen Activated Sludges	8-10	80-85	3-5 lbs/ton
High-Lime Sludges	50-55	90	no
Lime Classification	40	70	no

of 2-5 lbs per ton of dry solids. Dewatering of heat treated mixtures of activated sludge and raw primary sludge have produced cake solids of 40% at 95% recovery without chemicals. Dewatering of heat treated activated sludges alone has achieved 35% cake solids at 95% recovery without chemicals. The use of 4 lbs per ton of polymers in this latter case[33] enabled a 50% increase in centrifuge capacity while producing cake solids of 28%.

In addition to dewatering sludges, centrifuges have been used to separate impurities ("classify") from the lime sludges resulting from some phosphorus removal processes to enable efficient recovery and reuse of the lime.

Typical costs for centrifugation are presented in Table 10 based upon 4% influent solids concentration. Electrical requirements are a function of the bowl speed but are typically 200-400 kwh/ton of solids.

Centrifuges have the advantages of being a totally enclosed process and requiring less space than vacuum filters. They have the disadvantage of requiring more maintenance and more highly skilled maintenance.

Pressure Filtration

During the last five years, there has been a substantial increase in use of pressure filtration systems in U.S. wastewater plants. Improvements in the equipment involved coupled with increasing quantities of difficult-to-dewater sludges account for the increase.

The filter press is a batch device, which has been used in industry and in European wastewater plants for many years to process difficult-to-dewater sludges. There are several variations in mechanical design and operating pressures. For purposes of illustrating the concept, a vertical plate filter press system will be described. Such a press consists of vertical plates which are held rigidly in a frame and which are pressed together between a fixed and moving end as illustrated in Figure 8. On the face of each individual plate is mounted a filter cloth. The sludge is fed into the press and passes through the cloth, while the solids are retained and form a cake on the surface of the cloth. Sludge feeding occurs at pressures up to 225 psi and is stopped when the cavities or chambers between the trays are completely filled. Drainage ports are provided at the bottom of each press chamber. The filtrate is collected in these, taken to the end of the press, and discharged to a common drain. At the commencement of a processing cycle, the drainage from a large press can be in the order of 2,000 to 3,000 gallons per hour. This rate falls rapidly to about 500 gallons per hour as the cake begins formation and when the cake completely fills the chamber, the rate is virtually nothing. The dewatering step is completed when the filtrate is near zero. At this point the pump feeding sludge to the press is stopped and any back pressure in the piping is released through a bypass valve. The electrical closing gear is then operated to open the press. The individual plates are next moved in turn over the gap between the plates and the moving end. This allows the filter cakes to fall out. The plate moving step can be either

TABLE 10

ESTIMATED COSTS FOR DEWATERING BY CENTRIFUGE

Item	Tons Per Day of Dry Solids			
	10	25	50	100
Construction Cost	$360,000	$580,000	$ 860,000	$1,400,000
Engr., Legal, Adm., & Interest During Construction (19%)	68,400	110,200	163,400	266,000
Total Capital Cost	$428,400	$690,200	$1,023,400	$1,666,000
Labor, Operations at $10/Hr.	25,600	50,400	96,000	184,000
Labor, Maintenance at $10/Hr.	6,200	13,600	22,400	45,600
Maintenance Materials: Chemical	36,000	80,000	160,000	270,000
Maintenance Materials: Other	27,000	52,000	85,000	140,000
Annual O & M Costs	94,800	196,000	363,400	639,600
Annual Capital Costs (x .0944)	40,400	65,200	96,600	157,300
Total Annual Cost	$135,200	$261,200	$ 460,000	$ 796,900
Cost per ton of dry solids	$37.00	$28.60	$25.20	$21.80

Assumed: 4 % solids in influent

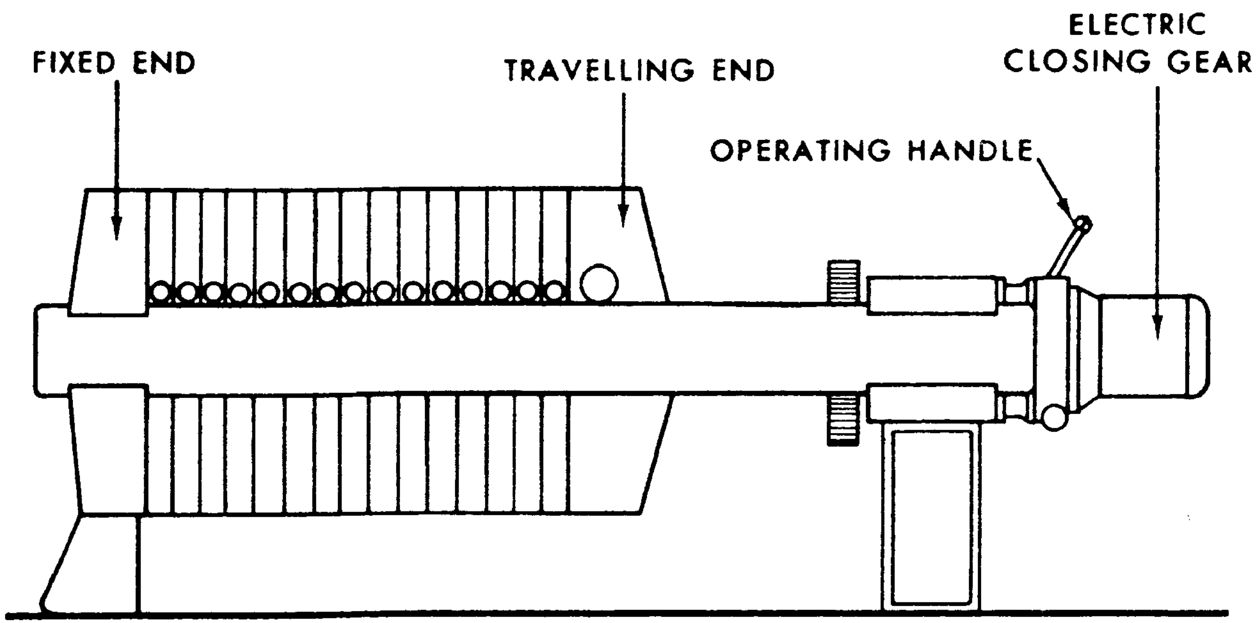


FIGURE 8 Side view of a filter press [47].

manual or automatic. When all the plates have been moved and the cakes released, the complete pack of plates is then pushed back by the moving end and closed by the electrical closing gear. The valve to the press is then opened, the sludge feed pump started, and the next dewatering cycle commences.

Filter presses are normally installed well above floor level, so that the cakes can drop onto conveyors or trailers positioned underneath the press. The pressures which may be applied to a sludge for removal of water by the filter presses now available range from 5,000 to 20,000 times the force of gravity. In comparison, a solid bowl centrifuge provides forces of 700-3,500 g and a vacuum filter, 1,000 g. As a result of these greater pressures, filter presses may provide higher cake solids concentrations (30-50% solids) at reduced chemical dosages. In some cases, ash from a downstream incinerator is recycled as a sludge conditioner.

Table 11 presents typical results from pressure filtration. As readily apparent, the process produces a drier cake than either vacuum filtration or centrifugation. Table 12 presents illustrative costs for the assumed conditions as defined in the Table. Although the dewatering costs are higher than for vacuum filters or centrifuges under comparable conditions, the drier cake produced may result in savings in the downstream process which are more than adequate to offset the higher costs. Electrical consumption is primarily a function of influent solids concentration and ranges from 100-200 kwh/ton of solids at 4% influent solids to 50-100 kwh/ton at 8% influent solids.

Drying Lagoons

Lagoon drying is a low cost, simple system for sludge dewatering that has been commonly used in the United States. Drying lagoons are similar to sandbeds in that the sludge is periodically removed and the lagoon refilled. Lagoons have seldom been used where the sludge is never removed, because such systems are limited in application to areas where large quantities of cheap land are available. Sludge is stabilized to reduce odor problems prior to dewatering in a drying lagoon. Odor problems can be greater than with sandbeds, because sludge in a lagoon retains more water for a longer period than does sludge on a conventional sand drying bed.

Other factors affecting design include consideration of groundwater protection and access control. Major design factors include climate, subsoil permeability, lagoon depth, loading rates, and sludge characteristics.

Solids loading rates suggested[4] for drying lagoons are 2.2 to 2.4 lb/yr/cu ft of lagoon capacity. Other recommendations range from 1 sq ft/capita for primary digested sludges in an arid climate to as high as 3 to 4 sq ft/capita for activated sludge plants where the annual rainfall is 36 inches. A dike height of about 2 feet with the depth of sludge after decanting of 15 inches has been used. Sludge depths of 2.5 to 4

TABLE 11

TYPICAL RESULTS
PRESSURE FILTRATION

Sludge Type	Conditioning	Percent Solids To Pressure Filter	Typical Cycle Length	Percent Solids Filter Cake
Primary	5% $FeCl_3$, 10% Lime	5	2 hours	45
	100% Ash		1.5	50
Primary + $FeCl_3$	10% Lime	4*	4	40
Primary + 2 stage high lime	None	7.5	1.5	50
Primary + WAS	5% $FeCl_3$, 10% Lime	8*	2.5	45
	150% Ash		2.0	50
Primary + (WAS + $FeCl_3$)	5% $FeCl_3$, 10% Lime	8*	3	45
(Primary + $FeCl_3$) + WAS	10% Lime	3.5*	4	40
WAS	7.5% $FeCl_3$, 15% Lime	5*	2.5	45
	250% Ash		2.0	50
WAS + $FeCl_3$	5% $FeCl_3$, 10% Lime	5*	3.5	45
Digested Primary	6% $FeCl_3$, 30% Lime	8	2	40
Digested Primary + WAS	5% $FeCl_3$, 10% Lime	6-8*	2	45
	100% Ash		1.5	50
Digested Primary + (WAS + $FeCl_3$)	5% $FeCl_3$, 10% Lime	6-8*	3	40
Tertiary Alum	10% Lime	4*	6	35
Tertiary Low Lime	None	8*	1.5	55

*Thickening used to achieve this solids concentration

TABLE 12

ESTIMATED COSTS FOR DEWATERING BY FILTER PRESS

Tons Per Day of Dry Solids	10	25	50	100
Construction Cost	$820,900	1,085,000	2,170,000	3,498,600
Engr., Legal, Adm., and Interest During Const. (19%)	156,000	206,200	412,300	664,700
Total Capital Cost	$976,900	1,291,200	2,582,300	4,163,300
Labor, O & M at $10/Hr.	76,000	120,000	180,000	310;000
Chemicals	46,000	100,000	180,000	310,000
Electric Power @ $0.025/Kwh	3,500	6,500	10,500	16,800
Sidestream Treatment, $8.80/T	32,000	80,000	160,000	320,000
Maintenance Materials at 3% of Capital Costs/Yr.	29,300	38,700	77,500	124,900
Annual O & M Costs	186,800	345,200	608,000	1,081,700
Annual Capital Costs (x .0944)	92,200	121,900	243,800	393,000
Total Annual Cost	$279,000	$467,100	$851,800	$1,474,700
Cost Per Ton of Dry Solids	$76.40	$51.20	$46.70	$40.40

Assumed: 5% $FeCl_3$, 10% Lime For Conditioning

2.4 hour cycle time

Cake solids = 40%

4% influent solids

feet may be used in warmer climates where longer drying periods are possible.

Sludge will generally not dewater in any reasonable period of time to the point that it can be lifted by a fork except in an extremely hot, arid climate. If sludge is placed in depths of 15 inches or less, it may be removed with a front-end loader in 3 to 5 months. When sludge is to be used for soil conditioning, it may be desirable to stockpile it for added drying before use. One proposed approach utilizes a 3-year cycle in which the lagoon is loaded for 1 year, dries for 18 months, is cleaned, and allowed to rest for 6 months. Definitive data on lagoon drying are scarce. Sludge may be dewatered from 5 percent solids to 40 to 45 percent solids in 2 to 3 years using sludge depths of 2 to 4 feet.

Limited cost data[32] on large lagoon systems indicate costs in the range of $10-20/ton exclusive of land costs.

INCINERATION

An incinerator is usually part of a sludge treatment system which includes sludge thickening, a macerating or disintegrating system, a dewatering device (such as a vacuum filter, centrifuge, or filter press), an incinerator feed system, air pollution control devices, ash handling facilities, and the related automatic controls. Important considerations in evaluating incineration methods include the composition of the sludge feed and the amount of auxiliary fuel required. Air pollution constraints and resultant equipment and treatment requirements as well as ash disposal are also important.

Of major interest from the standpoint of sludge incineration is the heat value of the sludge which is summarized in Table 13. The combustible portion of sewage sludge has a BTU content approximating that of lignite coal.

Incineration is a two-step process involving drying and combustion. In addition to fuel and air; time, temperature, and turbulence are necessary for a complete reaction. The drying step should not be confused with preliminary dewatering; dewatering is usually by mechanical means and precedes the incineration process in most systems. When a sludge with a moisture content of about 75 percent is delivered to the incinerators, (3 pounds of water for each pound of dry solids), the heat required to evaporate the water nearly balances the available heat from combustion of the dry solids.

Drying and combustion may be done in separate units or successively in the same unit. Manufacturers have developed diversified types of equipment. The two major incineration systems employed in the United States are the multiple hearth furnace and the fluidized bed incinerator (discussed later in this section). The drying and combustion process consists of the following phases: (a) raising the temperature of the feed sludge to 212°F, (b) evaporating water from the sludge, (c) increasing

TABLE 13

HIGH HEAT OF COMBUSTION OF SLUDGES* (TOTAL DRY SOLIDS BASIS)

From Reference (37)

Material	Combustibles (%)	Ash (%)	Average BTU/Pound*
Grease and scum	88.5	11.5	16,750
Raw sewage solids	74.0	26.0	10.285
Fine screenings	86.4	13.6	8,990
Ground garbage	84.8	15.2	8,245
Digested sewage solids and ground garbage	49.6	50.4	8,020
Digested sludge	59.6	40.4	5,290
Grit	33.2	69.8	4,000

*Moisture free basis

the water vapor and air temperature of the gas, and (d) increasing the temperature of the dried sludge volatiles to the ignition point. Practical operation of an incinerator requires that air in excess of theoretical requirements be supplied for complete combustion of the fuel. The introduction of excess air has the effect of reducing the burning temperature and increasing the heat losses from the furnace.

Heat is emitted by the burning of sludge in a furnace. Some of this heat is absorbed by the furnace and lost by radiation. A large portion of the emitted heat is lost with the stack gases, while a small portion is lost with the ash. The heat lost in the stack gas is available for recovery and reuse for purposes such as heating the incoming sludge and air.

There are a number of variables which influence the amount of fuel required and the resulting cost for sludge incineration. Principal variables are the moisture and volatile solids content of the sludge. Their effect on the amount of fuel required for incineration is shown by Figure 9. Temperatures of 1350-1400^{o}F are generally accepted as necessary to insure deodorization of the stack gases of a conventional incinerator. To insure complete thermal oxidation, it has been found necessary to maintain 50 to 100 percent excess air over the stoichiometric amount of air required in the combustion zone. This excess air is undesirable because it pirates 12 to 24 percent of the input BTU's for heating of the excess air. If excess air is not supplied, it is difficult to maintain the minimum deodorizing temperature. Therefore, a closely controlled minimum excess air flow is desirable for maximum thermal economy. The amount of excess air required varies with varies with the type of incineration equipment, the nature of the sludge to be incinerated, and the disposition of the stack gases. A closely controlled minimum excess air flow is desirable for maximum thermal economy. The impact of use of excess air on fuel required for sludge incineration is shown in Figure 10.

The stack gases leaving the incinerator represent a potential source of energy. By passing the gases through a heat exchanger, it is possible to extract heat for use in preheating the incoming furnace air, in sludge conditioning by heat treatment, or for other uses in the plant. Electricity can be generated by use of a boiler-generator system fueled by the stack gas heat. Figure 11 presents the potential for net recovery of heat by heat exchange equipment installed on a sludge incinerator. This analysis of heat recovered is independent of the type of incinerator used for combustion of sludge because only the combustion products or flue gases are considered. The potential for energy recovery from stack gases is significant. A detailed analysis[38] of a 30 mgd activated sludge plant showed that all of the electrical needs of the plant (about 8,300,000 kwh/yr) could meet by generating electricity form the incinerator stack gases (1400^{o}F initial flue gas temperature) from incineration of a 16% solids primary + WAS sludge. Whether or not this would be a cost-effective source of electrical energy would be dependent upon local conditions.

A heat treatment-incineration system has been proposed (and is being installed in 3 U.S. plants) which eliminates the need for any auxiliary

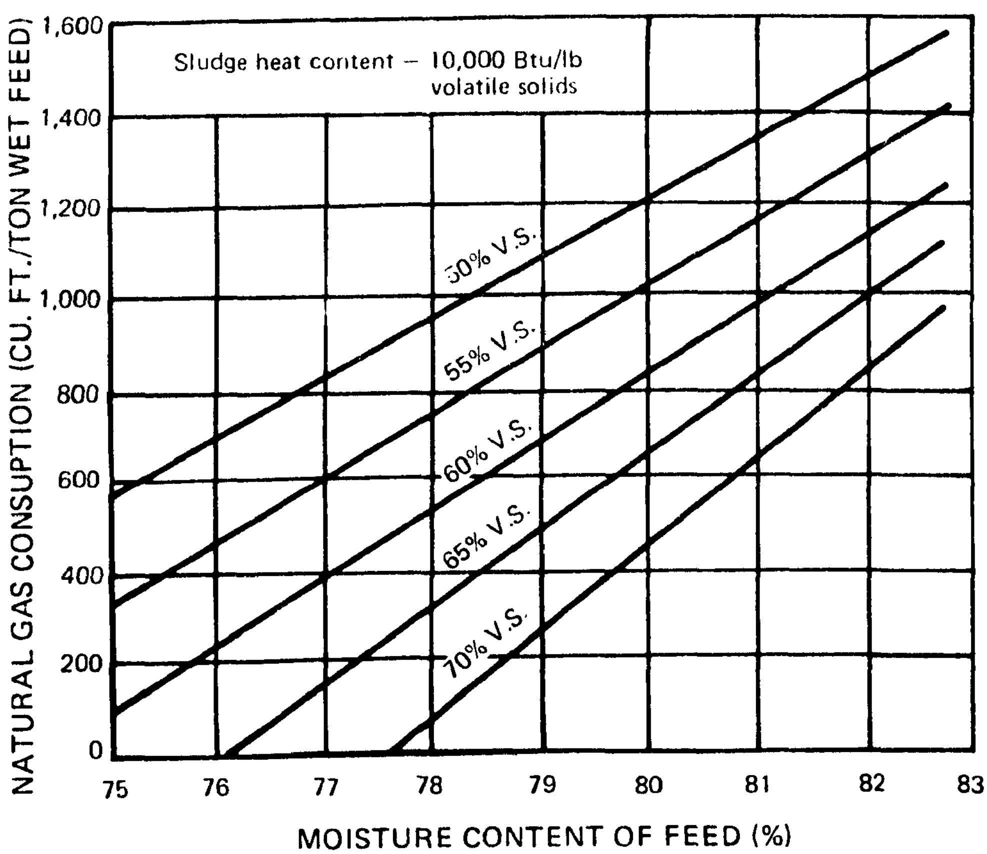
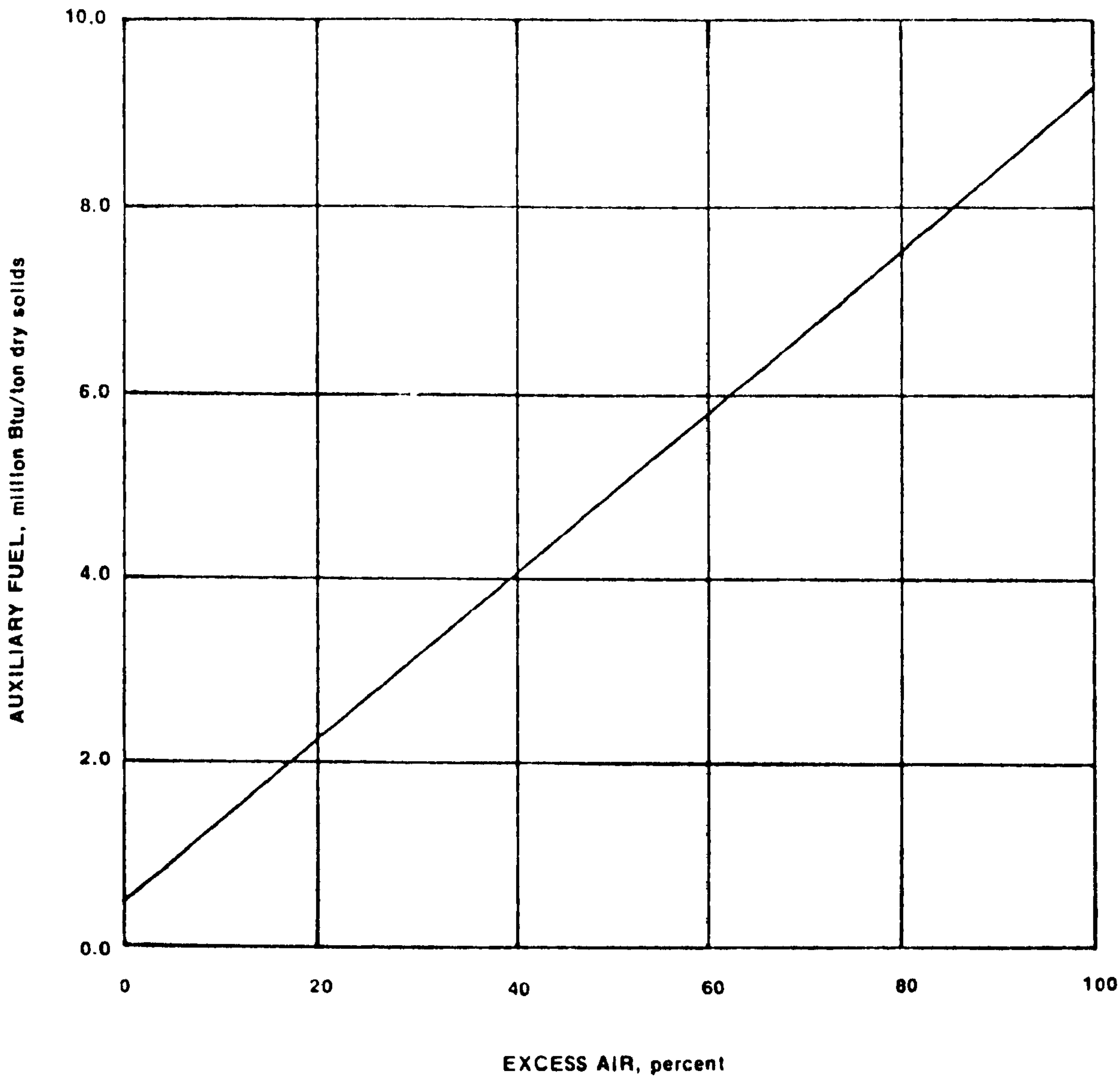


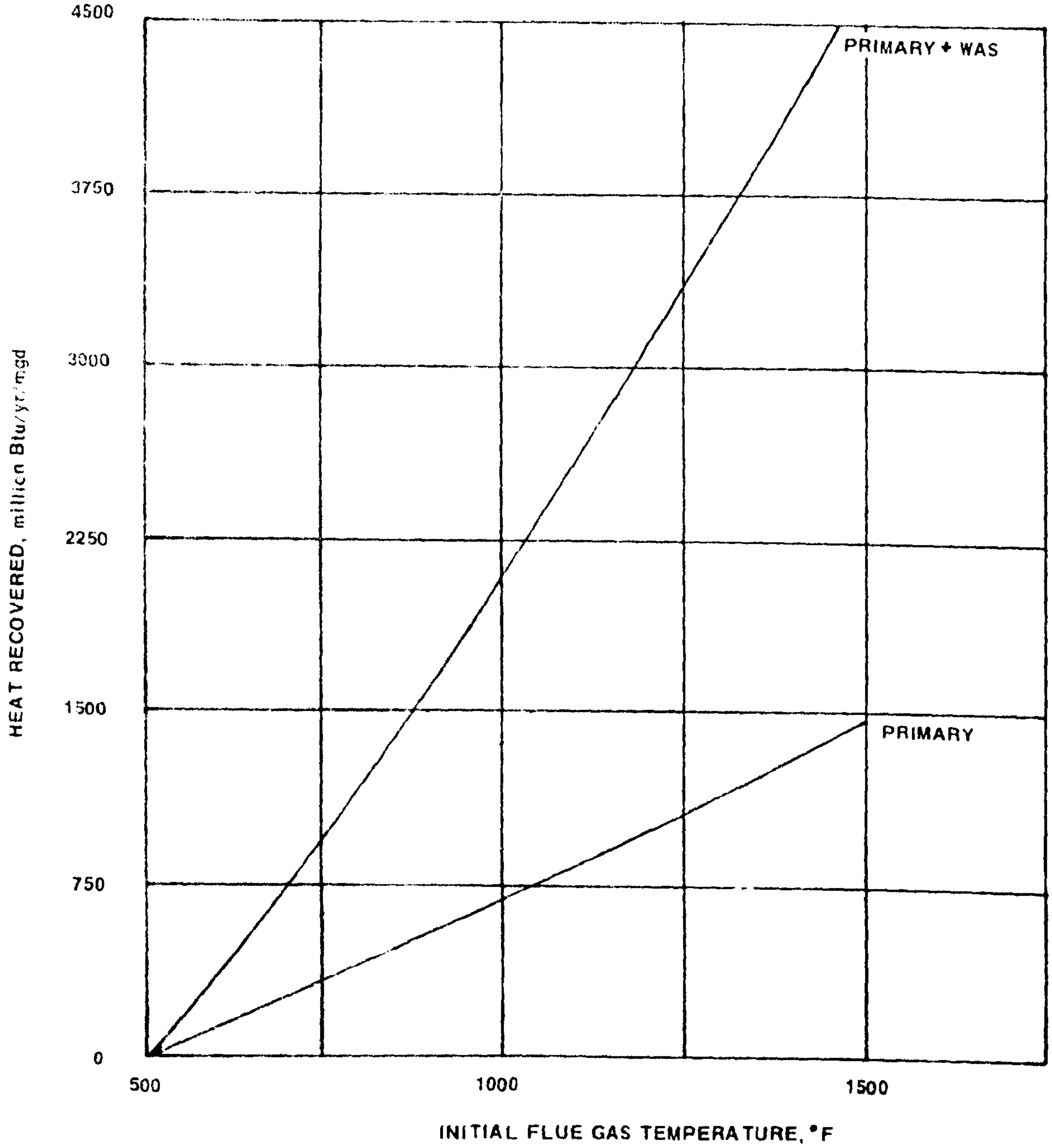
FIGURE 9. The effects of sludge moisture and volatile solids content on gas consumption.



Assumptions:
Solids: 30%
Exhaust Temp: 1500°F
Volatiles: 70%

IMPACT OF EXCESS AIR ON THE AMOUNT
OF AUXILIARY FUEL FOR SLUDGE INCINERATION

FIGURE 10



Assumptions:
Final Stack Temp = 500° F
50% excess air

(To convert Btu to kwh: 1 kwh = 10,500 Btu)

POTENTIAL HEAT RECOVERY FROM INCINERATION OF SLUDGE

FIGURE 11

fuels for the heat conditioning-incineration system[43]. The heat treatment conditioning enables an autogenous sludge cake to be achieved. As can be seen from Figure 12, heat production exceeds that required for combustion as typical primary + WAS concentrations exceed 25% solids (69% volatile). Solids concentrations of 30-40% are often achieved following heat treatment. Thus, there may be sufficient heat available in the stack gases to provide the heat needed for heat treatment which results in a self-sustaining sludge incineration system.

One approach to supplying the supplementary fuel needed for sludge incineration that has been suggested is to use solid wastes as fuel. The amount of solid waste required to sustain combustion of sludges is shown in Figure 13[38] based on 25% moisture in the solid waste and 4,750 BTU/lb of solid waste. Sludge with 5% solids and 70% volatile solids would require 28% refuse to sustain combustion.

The Kansas City metropolitan area is considering[85] incineration of 750-1,000 tons/day of shredded, air classified refuse and dried sludge (85% solids) for generation of electricity. Ferrous metals and possibly aluminum would be recovered. Use of a suspension-fired water wall incinerator and sale of the electricity provides a potential economic savings of about 28% over separate refuse disposal in a landfill.

Air pollution concerns must be addressed when considering incineration. Detailed data have been presented for several municipal sludge installations[4,39]. The major categories of concern are: particulates, metals, gaseous pollutants, and organic compounds.

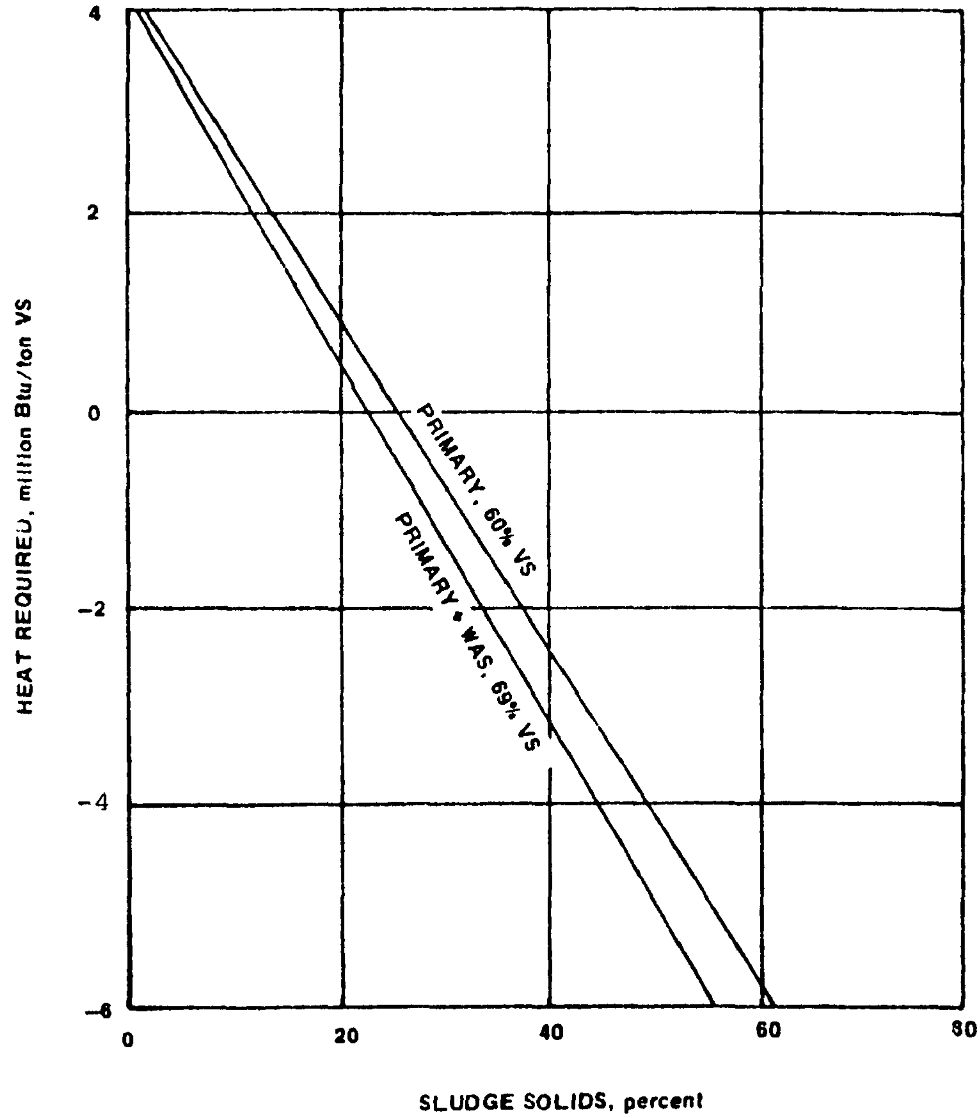
National air pollution standards for discharges from municipal sludge incinerators have been promulgated which limit emissions of particulates (including visible emissions) from incinerators used to burn wastewater sludge as follows[40]:

1. No more than 0.65 g/kg dry sludge input (1.30 lb/ton dry sludge input).

2. Less than 20 percent opacity.

Available data indicate that on the average, uncontrolled multiple hearth incinerator gases contain about 0.6 grain of particulate per standard cubic foot of dry gas[41]. Uncontrolled fluid bed reactor gases contain about 1.0 grain of particulate per standard cubic foot[11]. For average municipal wastewater sludge, this corresponds to about 33 pounds of particulates per ton of sludge burned in a multiple hearth, and about 45 pounds of particulates per ton of sludge burned in a fluid bed incinerator. Particulate collection efficiencies of 96 to 97 percent are required to meet the standard, based on the above uncontrolled emission rate. Venturi scrubbers have the demonstrated capability to meet the particulate discharge requirement without a significant increase in electrical power requirements[83].

Most metals present in municipal sludges are converted to oxides which appear in the particulates removed by the scrubber or in the ash.

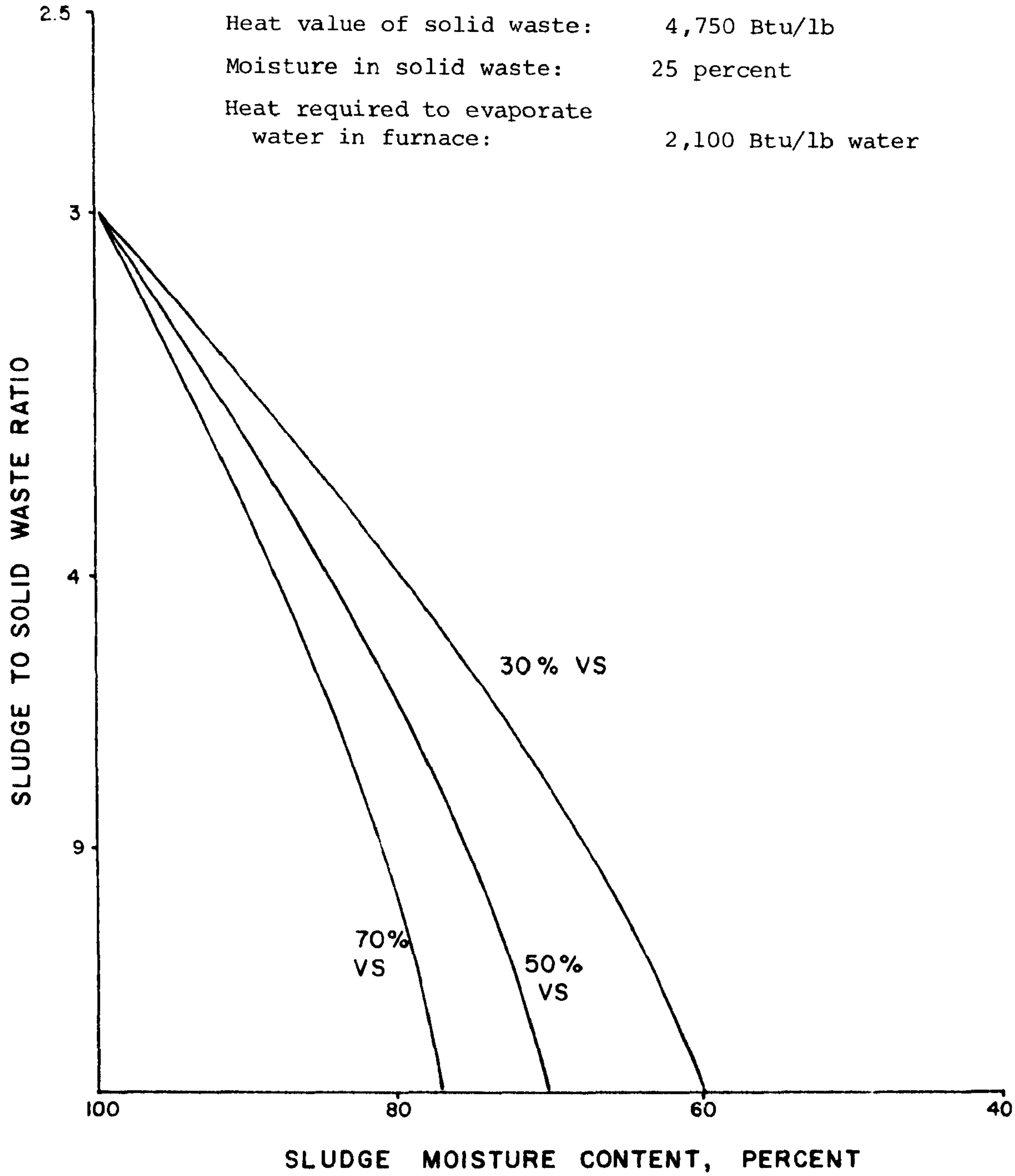


HEAT REQUIRED TO SUSTAIN
COMBUSTION OF SLUDGE

FIGURE 12

Assumptions:

Heat value of sludge:	10,000 Btu/lb VS
Heat value of solid waste:	4,750 Btu/lb
Moisture in solid waste:	25 percent
Heat required to evaporate water in furnace:	2,100 Btu/lb water



COMBUSTION OF SLUDGE AND SOLID WASTE

FIGURE 13

Lead and mercury are the only two metals which vaporize to an extent that the stack gas concentrations would be increased. However, it has been found that less than 15% of the lead and 2% of the mercury appear in the flue gas at the Palo Alto, Calif. sludge incinerator[43]. EPA has set a standard of 3200 gms/day of mercury for discharge from a sewage sludge incinerator. The Palo Alto incinerator discharge was only 6 gms/day. The per capita lead discharge was equivalent to the lead discharged from driving an auto using unleaded gas a distance of 200 ft/day. Metal discharges should not present a limitation as properly designed and operated municipal systems have met all air pollution standards for metals.

Gaseous pollutants could be released by sludge incineration are hydrogen chloride, sulfur dioxide, oxides of nitrogen, and carbon monoxide. Carbon monoxide is no threat if the incinerator is properly designed and operated. Hydrogen chloride, which would be generated by decomposition of certain plastics, is not a significant problem at concentrations currently observed. Consideration of the possibility of SO_2 and NO_x pollution is aided by examination of the sulfur and nitrogen content of sludges. Sulfur content is relatively low in most sludges. In addition, much of this sulfur is in the form of sulfate, which originated in the wastewater. Sulfur dioxide is not expected to be a serious problem. Sludge typically has a high nitrogen content from proteinaceous compounds and ammonium ion. Limited data are available for predicting whether a high proportion of these materials will be converted to oxides of nitrogen from sludge incineration should be less than 100 ppm from a properly operated incinerator and were observed to be less than 10 ppm from one facility tested by EPA[40]. Considering this low concentration, the production of oxides of nitrogen will probably not limit the use of incineration for disposing of sludge in most cases. The amount of NO_x per capita generated by a sludge incinerator has been equated to that generated by driving an auto less than 0.1 mile under the 1975 Federal NO_x Standards[43].

Toxic substances could be discharged from the organic substances - such as pesticides and PCB's - in the sludge. However, tests[39] have shown that total destruction of PCB's was possible when oxidized in combination with sewage sludge and with exhaust gas temperatures of 1100°F. Ninety-five percent destruction of PCB's was achieved in a multiple hearth furnace with no afterburning at exhaust temperatures of 700°F.

The EPA Sewage Sludge Incineration Task Force[42] concluded that it has been adequately demonstrated that existing well-designed and operated municipal wastewater sludge incinerators equipped with an adequate scrubbing system are capable of meeting the most stringent particulate emission control regulation existing in any state or local control agency. This observation coupled with the fact that the newly promulgated federal standards are based on demonstrated performance of an operating facility indicates that use of proper emission controls and proper operation of the incineration system will enable a facility to meet all existing air pollution regulations.

The volume reduction by sludge incineration is over 90% when compared to the volume of dewatered sludge. The ash from the incineration process is free of pesticides, viruses and pathogens. The metals in the ash are approximately at the same ratio as in the raw sludge; however, the metals are now in the less soluble oxide form. The ash can be readily transported in the dry state to appropriate landfill sites.

Multiple Hearth Incineration

The multiple hearth furnace is the most widely used wastewater sludge incinerator in the United States today, because it is simple, durable, and has the flexibility of burning a wide variety of materials even with fluctuations in the feed rate. A typical multiple hearth furnace is shown in Figure 14 and consists of a circular steel shell surrounding a number of solid refractory hearths and a central rotating shaft to which rabble arms are attached. The operating capacity of these furnaces is related to the total area of the enclosed hearths. They are designed with diameters ranging from 54 inches to 21 ft 6 inches and from four to eleven hearths. Capacities of multiple hearth furnaces vary from 200 to 8,000 lb/hr of dry sludge with operating temperatures as high as 1,700^{o}F. The dewatered sludge enters at the top through a flapgate and proceeds downward through the furnace from hearth to hearth through the rotary action of the rabble arms.

The estimated costs for incineration of 20% solids, (primary + WAS) are shown in Table 14. Fuel consumption is 8-10 x 10^6 BTU/TON of dry solids and electrical consumption is 50-90 kwh/ton of dry solids. Fuel consumption can be reduced by feeding a drier cake. The cost of achieving the drier cake must, of course, be balanced against the savings in incineration cost.

Fluidized Bed Incineration

The first fluidized bed wastewater sludge incinerator was installed in 1962, and there are now several units operating. They range in size from 220 to 5,000 lb/hr dry solids. A typical section of a fluid bed reactor used for combustion of wastewater sludges is shown in Figure 15. The fluidized bed incinerator is a vertical cylindrical vessel with a grid in the lower section to support a sandbed. Dewatered sludge is injected above the grid and combustion air flows upward at a pressure of 3.5 to 5.0 psig and fluidizes the mixture of hot sand and sludge. Supplemental fuel can be supplied by burners above or below the grid. In essence, the reactor is a single chamber unit where both moisture evaporation and combustion occur at 1,400 to 1,500^{o}F in the sandbed. All the combustion gases pass through the 1,500^{o}F combustion zone with residence times of several seconds. Ash is carried out the top with combustion exhaust and is removed by air pollution control devices.

The quantities of excess air are maintained at 20 to 25 percent to minimize its effect on fuel costs as was illustrated by Figure 10. The heat reservoir provided by the sandbed enables reduced start-up times when the unit is shut down for relatively short periods (overnight). As an example, a unit can be operated 4 to 8 hours a day with little reheating when restarting, because the sandbed serves as a heat reservoir.

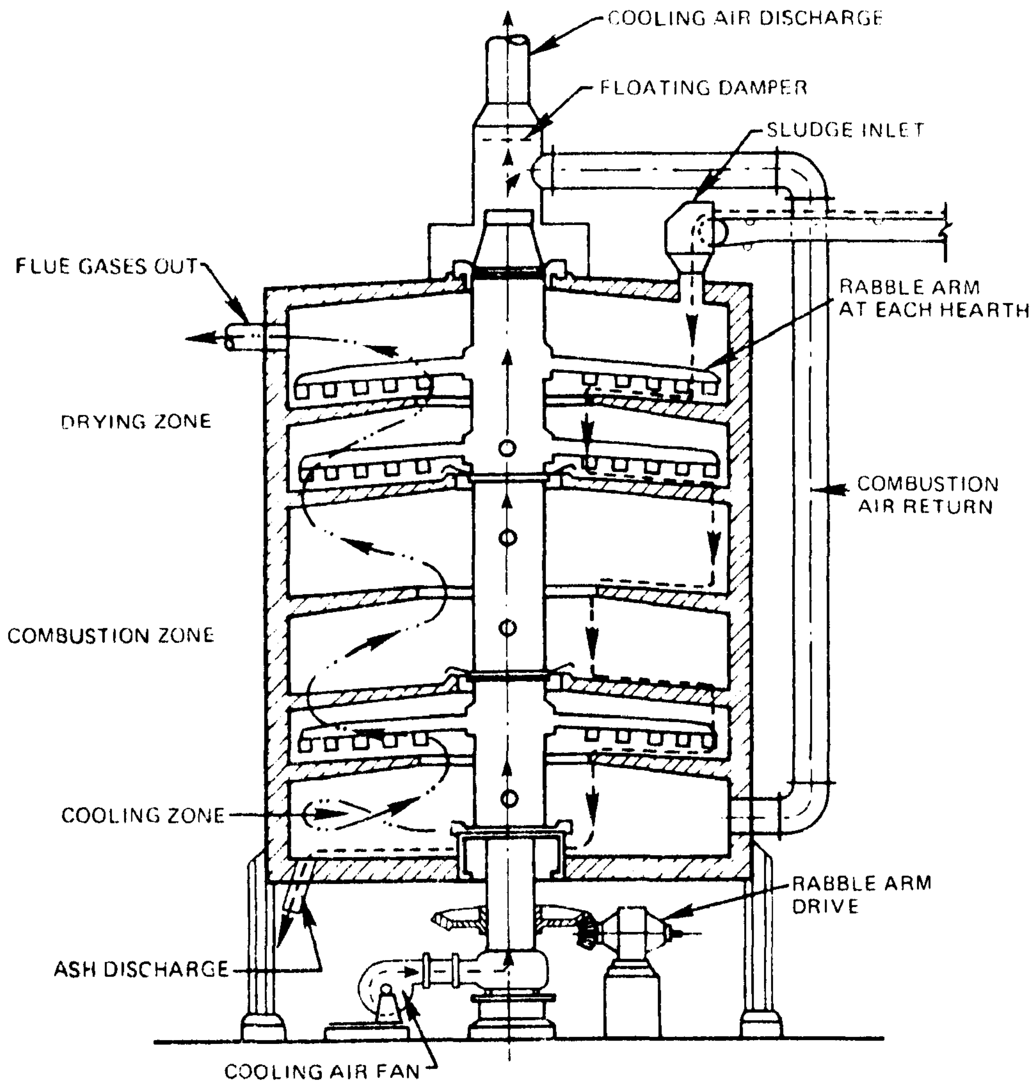


FIGURE 14 Cross section of a typical multiple hearth incinerator.

TABLE 14

ESTIMATED COSTS OF SLUDGE INCINERATION

Item	Tons Per Day of Dry Solids 10	25	50	100
Construction Cost	$1,800,000	$2,200,000	$3,000,000	$5,000,000
Engr., Legal, Adm., & Interest During Construction (19%)	342,000	418,000	570,000	950,000
Total Capital Cost	$2,142,000	$2,618,000	$3,570,000	$5,950,000
Labor, At $10/Hr.	40,000	55,000	95,000	140,000
Fuel @ $3/M Btu	90,000	210,000	420,000	840,000
Electric Power @ $0.025/Kwh	8,000	16,500	27,500	47,500
Maintenance Materials	8,000	15,000	25,000	42,000
Annual O & M Costs	$ 146,000	$ 296,500	$ 567,500	$1,069,500
Annual Capital Costs (x .0944)	202,200	247,100	337,000	562,000
Total Annual Cost	$ 348,200	$ 543,600	$ 904,500	$1,631,500
Cost Per Ton of Dry Solids	$95.39	$59.57	$49.56	$44.70

Assumption:

20% solids, Primary + WAS

Combustion Temperature = 1400°F

Furnace Operated 70% of the time (Start-up fuel included)

Does not include cost of dewatering prior to incineration

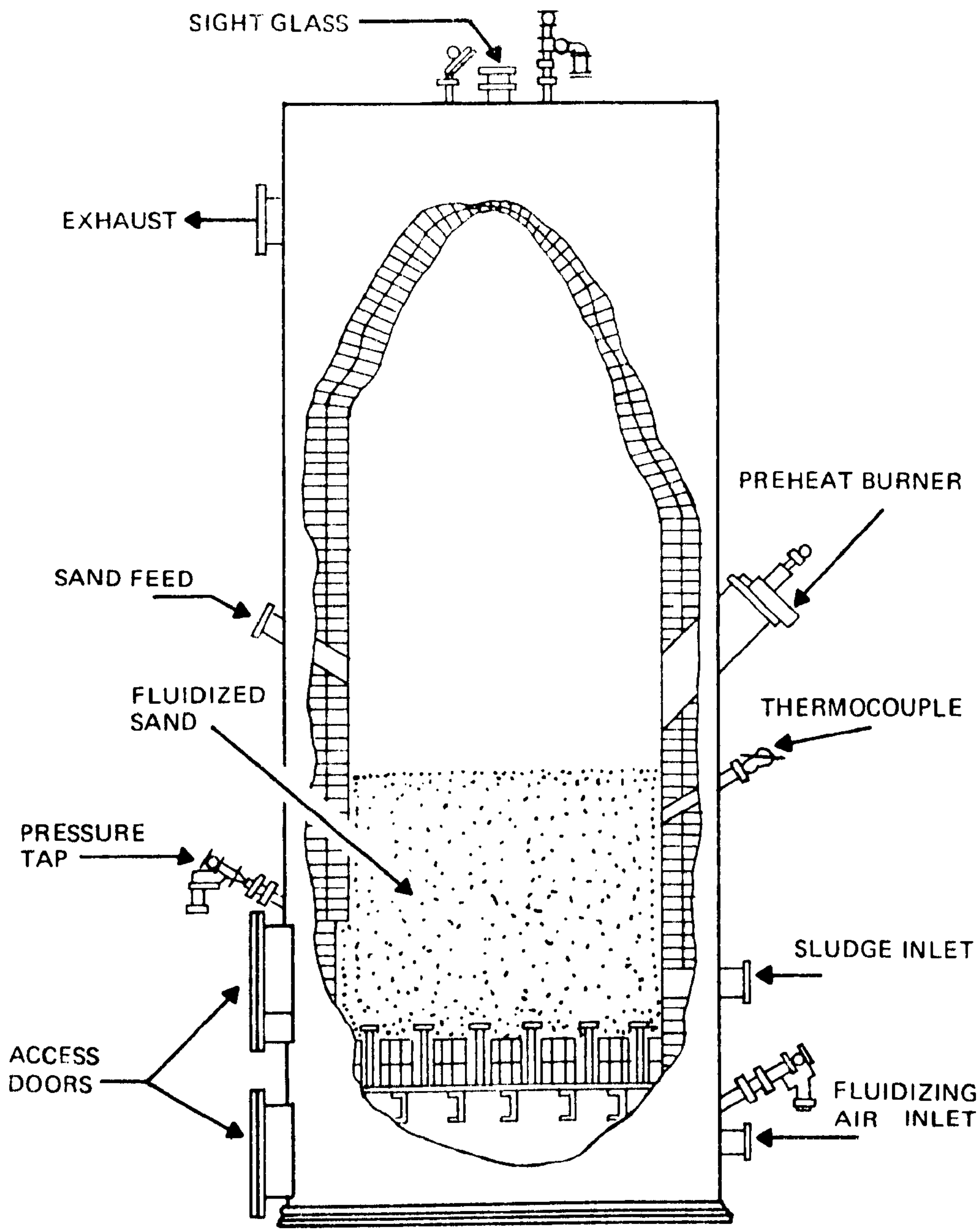


FIGURE 15 Cross section of a fluid bed reactor.

Exhaust gases are usually scrubbed with treatment plant effluent and ash solids are separated from the liquid in a hydrocyclone, with the liquid stream returned to the head of the plant.

Actual field cost data on fluidized bed systems for municipal sludges are limited. They are often competitive with multiple hearth systems on capital costs but typically have somewhat higher O & M costs. Electrical requirements are substantially higher than multiple hearth furnaces.

Wet Air Oxidation

The heat treatment, sludge conditioning system illustrated in Figure 2 can be used for sludge reduction of oxidation by operation at higher temperatures (350-400°F) and higher pressures (1200 psig). The wet air oxidation (WAO) process is based on the fact that any substance capable of burning can be oxidized in the presence of liquid water at temperatures between 250°F and 700°F. Wet air oxidation does not require preliminary dewatering or drying as required by conventional combustion processes. However, the oxidized ash must be separated from the water by vacuum filtration, centrifugation, or some other solids separation technique. Air pollution is minimized because the oxidation takes place in water at low temperatures and no flyash, dust, sulfur dioxide or nitrogen oxides are formed.

The problems noted earlier in the heat treatment discussion related to recycle of high-strength liquors to the wastewater treatment plant, the presence of refractory materials, high maintenance, and odor control also exist for the WAO application. The high pressure-temperature system also introduces some significant safety concerns. The cost of the system for sludge reduction is usually higher than competitive reduction systems[45]. Use of heat treatment for sludge conditioning is more widespread than use of WAO as a reduction process.

Lime Recalcining

Lime if often used as a coagulant either as a tertiary step or ahead of the primary clarifier in either a biological or a physical-chemical plant for removal of phosphorus form wastewaters. There is, of course, considerable experience around the world with the successful recalcining and reuse of lime used in water treatment plants and these techniques may also be used to recalcine and reuse lime in wastewater applications.

The process of recalcining consists of heating the dewatered calcium-containing sludge to about 1,850°F which drives off water and carbon dioxide leaving only the calcium oxide (or quicklime). Either multiple hearth or fluidized bed furnaces may be used for recalcining. Recovery and reuse of the lime reduces the amount of chemical sludge requiring disposal by a factor of about 20. The significant savings in sludge disposal costs may offset enough of the costs of lime recalcining costs to make the economics attractive. The economic feasibility of lime recalcining must be carefully evaluated for each locale, however. In cases where there are acceptable sludge landfill sites, it has proven to be cost effective to dewater the lime sludges and bury them rather than recover them by recalcining.

Table 15 presents illustrative recalcining costs. Costs do not include dewatering since dewatering costs would be common with disposal alternatives.

Fuel costs, as can be seen from Table 15, have a major impact on recalcining costs and can indeed be the determining factor in recalcining feasibility. In some parts of the country, fuel oil costs exceed the $3/MBTU used in Table 15, while in others, natural gas may be available at $1.50/MBTU. The impact of the $1.50/MBTU fuel costs is illustrated by the last line in Table 15. Makeup lime costs have increased sharply as a result of recent fuel cost increases. A cost of $51.50/ton of lime was quoted for delivery in the Los Angeles area on December 27, 1976. As indicated in Table 15, the cost of recalcined lime approaches that of fresh lime at 100 tons/day of chemical sludge.

For a situation where there are 25 tons/day (dry solids) of chemical sludges generated, the following calculations illustrate some considerations in evaluating the break-even point for costs of recalcining:

Daily Costs With Recalcining:	at $3/MBTU	at $1.50/MBTU
Incineration Costs, 25 Tons/Day	$1,457.50	$1,169.84
Make Up Lime, 3.75 Tons/Day @ $50/Ton	187.50	187.50
	$1,645.00	$1,357.34
Daily Costs Without Recalcining:		
Lime, 18.8 Tons/Day @ $50/Ton	- $ 940.00	$ 940.00
Break Even Costs for Sludge Disposal	$ 705.00	$ 417.34
÷ 25T/DAY =	$28.20/TON	$16.70/TON

In a real-life case, there may be other elements affected by the recalcining decision. For example: dewatering costs may differ; other chemical feed costs (i.e., polymers) may differ, etc. The cost effects on these other elements would, of course, be included in an analysis of recalcining economic feasibility.

For the illustrative example, if the 25 tons/day (dry basis) of 50% solids chemical sludge can be disposed of for $28.20/TON or less, economics would not favor recalcining at $3/MBTU. At $1.50/MBTU, the breakeven point is $16.70/TON for disposal of the dewatered sludge.

A detailed discussion of lime recalcining systems and costs is available[46].

Pyrolysis

There is a recent surge of interest in pyrolysis as a means of disposing

TABLE 15

ESTIMATED COSTS OF LIME RECALCINING

Item	Tons Per Day of Dry Solids 10	25	50	100
Construction Cost	$1,400,000	$2,000,000	$2,800,000	$4,000,000
Engr., Legal, Adm., & Interest During Constr. (19%)	266,000	380,000	532,000	760,000
Total Capital Cost	$1,666,000	$2,380,000	$3,332,000	$4,760,000
Labor @ $10/Hr	40,000	70,000	120,000	200,000
Fuel @ $3/MBTU	95,000	210,000	450,000	810,000
Power @ $0.025/kwh	7,500	15,000	25,000	50,000
Maintenance Materials	8,000	12,000	20,000	30,000
Annual O & M Costs	$ 150,500	$ 307,000	$ 615,000	$1,090,000
Annual Capital Costs (x .0944)	157,000	225,000	315,000	449,000
Total Annual Cost	$ 307,500	$ 532,000	$ 930,000	$1,539,000
Cost Per Ton of Dry Solids	$84.24	$58.30	$50.95	$42.16
Cost Per Ton of Recovered CaO	$135.00	$93.28	$81.53	$67.46
Cost Per Ton of Recovered CaO of Fuel = $1.50/MBTU	$113.98	$74.87	$61.80	$49.70

Assumptions: Coagulation of Secondary Effluent

7 psf/hr (wet) loading rate

20% downtime

50% solids in furnace feed

Multiple Hearth Furnace

Lime Dosage = 400 mg/l as CaO

Lime Recovery = 80%

Does not include cost of dewatering prior to recalcining of sewage sludge. This has come about as a result of the apparent need for new and improved processes and equipment in the practice of sludge disposal and the possibility that pyrolysis may offer an alternative to incineration which may be lower in cost, use less fuel, provide improved air pollution control, and afford greater heat recovery, under certain conditions.

Pyrolysis is a process in which organic material is decomposed at high temperature in an oxygen-deficient environment. The action, causing an irreversible chemical change, produces three types of products: gas, oil and char (solid residue). Water vapor is also produced, usually in relatively large amounts depending on the initial moisture content of the materials being pyrolysed. Residence time, temperature and pressure in the reactor are controlled to produce various combinations and compositions of the products. Two general types of pyrolysis processes may be used. The first, true pyrolysis, involves applying all required heat external to the reaction chamber. The other, sometimes called partial combustion and gasification, involves the addition of small amount of air or oxygen directly into the reactor. The oxygen sustains combustion of a portion of the reactor contents which in turn produces the heat required to dry and pyrolyse the remainder of the contents.

Pyrolysis of municipal refuse and of sewage sludge has been considered as a means for ultimate disposal of wastes for several years(47-50). The results of various studies and pilot programs indicate that if the moisture content of a sludge is below 70 to 75 percent, enough heat can be generated by combustion of the oil and gases produced from the pyrolysis of sludge for the process to be thermally sustaining. Pyrolysis of municipal refuse, and combinations of refuse and wastewater sludges will provide energy in excess of that required in the pyrolytic process(48,50).

Laboratory, pilot and demonstration systems for pyrolysis of wastewater sludges have been tested but no full-scale systems are in operation. Therefore, data presented must be considered preliminary. Pryolysis systems are in the developmental stages and additional information will become available as research and development work and the operation of full-scale plants progresses.

The BSP Division of Envirotech Corporation and others have conducted research and development work on using multiple hearth furnaces, similar in design to conventional sludge incinerators, for pyrolysis of wastewater sludges mixed with municipal solid wastes. A 100 ton/day unit is being installed at Concord, California(84). Shredded and classified solid wastes and dewatered sludge are fed to the furnace either in a mixture or separately with the wetter sludge fed higher in the furnace. Recirculated hot shaft cooling air and supplemental outside combustion air are fed to the lower hearths to sustain partial combustion of the wastes circulating down through the furnace. Fuel gas produced through the pyrolysis reaction is then burned in a high temperature afterburner. The resulting heat can be used in a waste heat boiler to produce high pressure steam. It may also be possible to burn the fuel gases directly in a boiler. Char from the process is not used but, because it has some fuel value, it may be usable as an industrial fuel.

The multiple hearth process offers the following advantages: (1) usable in much smaller plants than most other pyrolysis systems, (2) employs modifications of well developed sludge incineration equipment, (3) produces high temperature gases without raising temperatures in the solid phase to the slagging point, and (4) conversion from existing conventional sludge incineration systems is a relatively simple procedure. Disadvantages include: (1) fuel value of the char is not used, (2) high temperature fuel gases must be used on-site, and (3) incoming solid wastes must be well classified.

It is estimated that this process will produce between 2 and 2.5 tons of steam from one ton of a 2:1 mixture of municipal solid waste and sludge.

Table 16 summarizes the status of the several independent efforts in the area of pyrolysis (solid waste) or co-pyrolysis (sludge plus solid waste) now underway. The following paragraphs describe some of the more fully developed systems.

Landgard Process - In this process, shredded waste materials are heated indirectly by combusting a portion of the pyrolytic gases produced in a rotary kiln reactor. The remaining gases are burned to produce steam in a utility boiler. The char is not combusted and requires disposal, however, it does have characteristics similar to some activated carbons and eventually may be usable. Residue discharged from the kiln is water-quenched and then treated by flotation to separate the char from metal and glass wastes. The off-gases from the reactor are drawn into a waste gas burner where they are burned in air. The hot exhaust gases from the burner than pass through a water-tube boiler and then through a final cooler and air pollution control equipment. Operating on municipal solid wastes, the process will produce slightly less than 2.5 tons of steam per ton of waste.

Purox System - The Union Carbide Purox system is a gasification or partial combustion process which maximizes gas production. Unshredded waste materials are charged into the top of a vertical shaft furnace. The char is combusted by injecting pure oxygen at the bottom of the furnace. Hot combustion gases, essentially free of oxygen, rise through furnace and pyrolyse the descending wastes into fuel gas, oil and additional char. The resulting gaseous mixture rises further, drying the incoming wastes. Water and oil are condensed from the gaseous stream which is then cleaned for use. The condensed oil is returned to the furnace for combustion and further production of gas. The end result is a clean-burning fuel with a heat value of about 300 to 500 Btu/scf produced at a rate of about 7.5 million Btu/ton of solid waste. This system will receive unprocessed trash and, as a result of the high combustion temperature of the char, produce a molten metal and glass slag. The slag is water-quenched and reportedly is suitable for use as a construction fill material.

TABLE 16

MUNICIPAL SOLID WASTE AND SEWAGE SLUDGE

PYROLYSIS PROCESSES

Developer	Products	Pilot Plant Scale	First Major Demonstration Plant
Monsanto Envirochem Systems Inc., St. Louis, Mo. (Landgard)	Fuel Gas or Steam, Ferrous Metal, Wet Char, Glass Aggregate	36 ton/day	1000 ton/day solid wastes (Baltimore, MD) co-pyrolysis considered
Occidental Research Corp. (formerly Garrett), La Verne, Calif.	Pyrolytic Oil, Char, Glass, Ferrous Metal, Nonferrous Metal, Organics in Condensate	4 ton/day	200 ton/day solid wastes; start-up schedule for late 1976 (San Diego, CA)
Union Carbide Corp., New York, N. Y. (Purox)	Fuel Gas, Slag	200 ton/day	Solid waste; scheduled for co-pyrolysis. Pilot plant still in operation late 1976 (S. Charleston, WV)
Carborundum Environmental Systems, Inc., Niagara Falls, N. Y. (Torrax)	Steam (or Fuel Gas), Slag	75 ton/day	200 ton/day commercial plant under construction in Europe (Andco, Inc.)
BSP Division Envirotech Belmont, California	Steam (Fuel Gas)	100 ton/day	Co-pyrolysis (Concord, CA)
Jet Propulsion Laboratory, California Institute of Technology Pasadena, California	Activated Carbon and Fuel Gas	Initial pilot plant operated at 10,000 gpd - sewage	1 mgd pilot plant in operation (Fountain Valley, CA)
Battelle Pacific Northwest Laboratories, Richland, Washington	Steam (or Fuel Gas)	2 ton/day; 150 ton/day demonstration plant under consideration	---
Pyrolytic Systems, Inc. Riverside, Calif.	Fuel Gas or Electric Power	50 ton/day by late 1976	---
DEVCO Management, Inc. New York, N.Y.	Fuel Gas	50 ton/day	---
Pollution Control, Ltd. Copenhagen, Denmark	Fuel Gas	5 ton/day	---
Urban Research & Development Corp., East Granby, Conn.	Slag, Fuel Gas	120 ton/day	---

Occidental Process - Occidental Research Corporation has developed a process that produces oil as its main product. A finely divided, organic feed is supplied to the pyrolysis reactor. Dividing is accomplished in a two-stage shredding operation which also reduces the inorganic content of raw refuse through air classification and screening to less than 4 percent by weight. The process, using the finely divided feed, permits flash pyrolysis at atmospheric pressure for maximum oil production. Discharge from the reactor goes first to a char separator and then to a gas-liquid separator where gases and water are separated from the oil.

The relatively small amount of char and gases produced are recycled to produce heat for the reaction. The pyrolytic oil produced has a heating value of about 10,5000 Btu/lb and about 0.2 tons of oil are produced per ton of solid waste processed. This oil is best utilized by blending with No. 6 fuel oil for use in utility boilers and has the advantage of being storable and transportable.

Torrax System - The Carborundum Torrax system is somewhat similar in concept to the Purox system. Char is combusted to provide the heat necessary for pyrolysis. However, air, not pure oxygen, is supplied to support combustion. The result is diluted fuel gas with a low heating value (120-150 Btu/scf) best utilized by combustion on-site to produce steam.

Estimates of the potential energy production from pyrolysis of refuse and sludge combined have been made for the Landgard and Purox systems[38]. These systems should be representative of most pyrolysis systems since the main interest is in a heat balance for the overall concept and not in the unit heating values for an individual product. Process differences result in variations in the composition and quantities of fuel produced, but should result in relatively minor variations in net heat output.

The estimates made indicate that the pyrolysis process would be self-sustaining from an energy standpoint with mixtures of sludge and solid waste containing 25%-40% sludge and 60%-75% solid wastes. The refuse to sludge ratio for a typical residential community is in the range of 10:1 to 15:1 on a dry solids basis and 3:1 to 8:1 on a wet solids basis, indicating that more than enough refuse is generally available for mixing with sludge to operate the process without the need for an external energy source.

Pyrolysis appears to have several advantages over incineration. For example, some pyrolysis processes can convert wastes to storable, transportable fuels such as fuel gas or oil while incineration only produces heat that must be converted to steam. Pyrolysis gives a 50 percent greater reduction in volume of residue over incineration and the residue is a more readily usable by-product. Air pollution is not as severe a problem in pyrolysis systems because the volume of stack gases and the quantity of particulates in the stack gases are less.

On the other hand, pyrolysis is essentially still in the developmental stage and, with few exceptions, viable commercial systems are not readily available. Most of the pyrolytic fuel gases have relatively low heat values and the pyrolytic oil is corrosive, requiring it to be mixed with other fuel oil for best results.

The construction and operating costs for most pyrolysis systems are much more uncertain than for incineration. Reliable cost data for pyrolysis systems will not be available until significant operating experience is developed from the ongoing and planned demonstration projects.

DRYING OF SLUDGE

Flash Drying

Flash drying is the instantaneous removal of moisture from solids by introducing them into a hot gas stream. This process was first applied to the drying of wastewater sludge at the Chicago Sanitary District in 1932. A flow diagram of the process is shown in Figure 16[52]. Originally, units were designed to dry sludge for fertilizer and burn only the excess. The system is based on three distinct cycles which can be combined in different arrangements. The first cycle is the flash drying cycle, where wet filter cake is blended with some previously dried sludge in a mixer to improve pneumatic conveyance. The blended sludge and the hot gases from the furnace at 1,300°F are mixed ahead of the cage mill and flashing of the water vapor begins. The cage mill mechanically agitates the mixture of sludge and gas and the drying is virtually complete by the time the sludge leaves the cage mill. The sludge, at this stage, is at a moisture content of 8 to 10 percent and dry sludge is separated from the spent drying gases in a cyclone. The dried sludge can be sent either to fertilizer storage or to the furnace for incineration.

The second cycle is the incineration cycle. Combustion of fuel is essential to provide heat for drying the sludge and the fuel may be gas, oil, coal, or wastewater sludge. Primary combustion air, provided by the combustion air fan, is preheated and introduced at a high velocity to promote complete sludge combustion.

The third cycle is the effluent gas cycle or induced draft cycle consisting of the deodorizing and combustion air preheaters, dust collector, induced draft fan, and stack. Heat recovery is practiced to improve economy. The effluent gases then pass through a dust collector (dry centrifuge or wet scrubber) and the induced fan discharges the effluent gases through a stack into the atmosphere.

Perhaps the most notable current United States usage of this process is that by the City of Houston, Texas[52] primarily for drying sludge for use as a fertilizer. The dry product after complete processing has a moisture content of around 5.5 percent. From analysis at the time of sales of fertilizer in January, 1972, the moisture content was 5.0 percent; ash 34.76 percent; nitrogen 5.34 percent; and available phosphoric acid, 3.93 percent. The ash content fluctuates; the lowest on record is

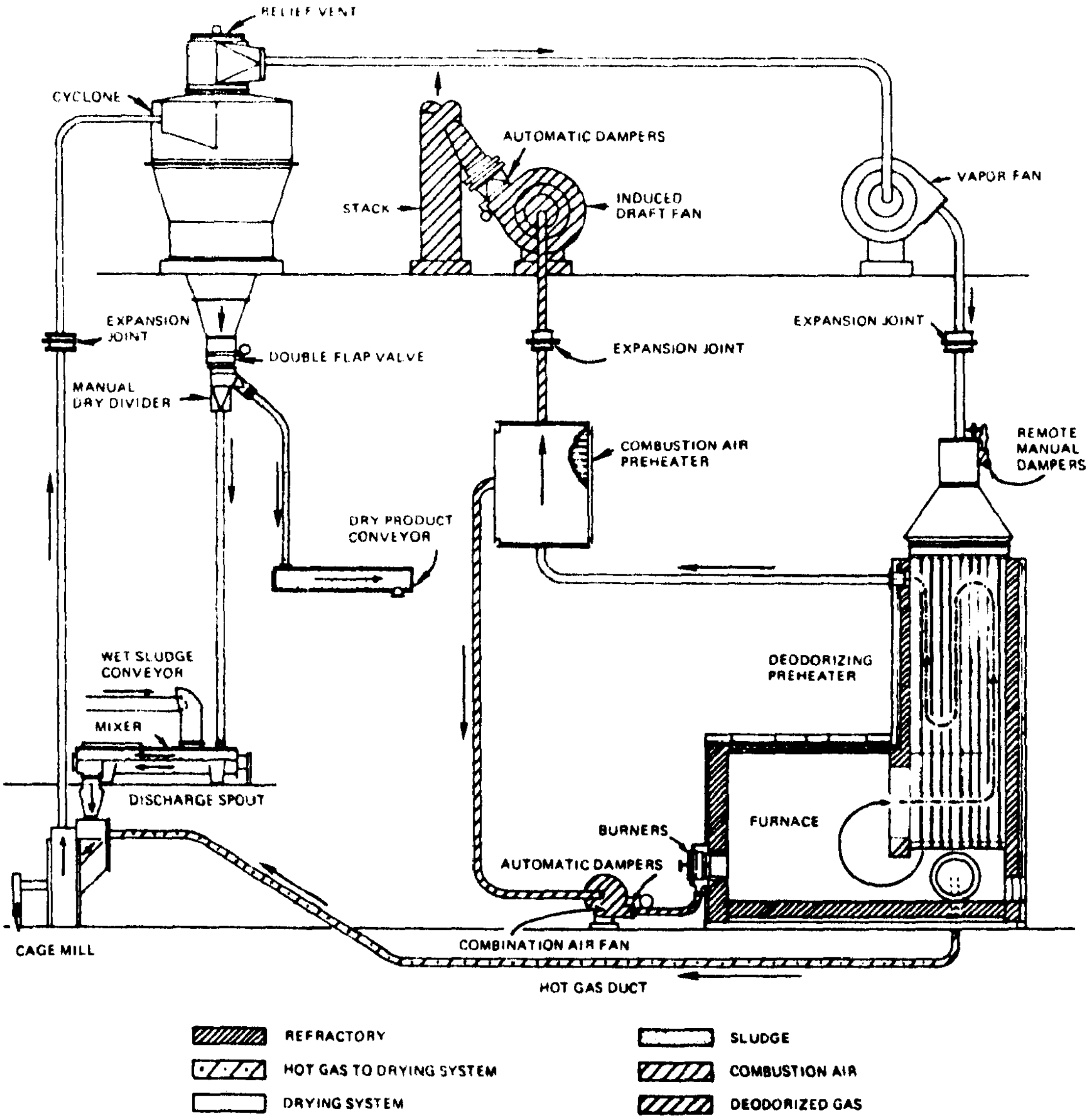


FIGURE 16. Flash dryer system [52]

26.4 percent and highest, 44.3. Throughout the experience with this operation, the city's marketing arrangements have been scheduled on the basis of competitive bidding. The successful bidder is committed to placing orders with the city for its entire production for the contract period of five years. The material is shipped in bulk by railroad car lots or sometimes by barge. It is bagged for resale at the point of arrival. The present contractor has been handling it for about 10 years, disposing of about 80 percent of the production in the citrus groves of Florida. There has never been a time when it was not possible to dispose of the entire sludge production by sales.

The use of the flash drying systems for incineration alone has not proven attractive. The Metropolitan Denver Sewage Disposal District No. 1 plant (approximately 100 mgd in capacity) abandoned a system of this type due to air pollution and problems of continuing explosions in the units. As an incineration unit, the flash drying system has the disadvantages of complexity, potential for explosions, and potential for air pollution by fine particles. An advantage is the flexibility it offers for drying a portion of the sludge for fertilizer.

Flash drying is relatively expensive because of fuel costs (contrasted to incineration - no heating value is realized from the sludge) and because pretreatment needs for production of sludge, which must have some reasonable nutrient balance, are also expensive. Fuel consumption for production of dried sludge is about 8,000 BTU/lb for flash drying.

Many flash drying installations have been abandoned due to high costs (typically twice or more the cost for incineration and heat recovery), odor problems, and the problems (air pollution and explosions) associated with the fine particulates.

Another approach to heat drying of wastewater sludges for use as fertilizers has been studied at the Blue Plains plant in Washington, D.C.[51]. A schematic of the system is shown in Figure 17. Drying is achieved in a jet mill in this case. The mill has no moving parts and offers the ability to dry and classify solids simultaneously.

Sludge is dried and sterilized at a temperature of 1100°F. In order to obtain a fertilizer with the desired nutrient balance at the Blue Plains plant, it has been necessary to supplement the nitrogen content of the sludge. The resulting product being marketed under the trade name, OrganaGro, contains 6 percent nitrogen, 4 percent phosphoric acid, and no potash.

During the system's break-in phase, more than 15,000 tons of sludge were processed, at a running rate 200-270 wet tons of sludge per day, with production of dry product per day being 40-54 tons[51]. The solids content of the feed sludge averaged 22 percent. Operation and maintenance problems have resulted in the temporary shut-down of this unit at the Blue Plains plant. Trash and fibrous material from the primary clarifiers has caused problems of fires and materials handling. Very serious

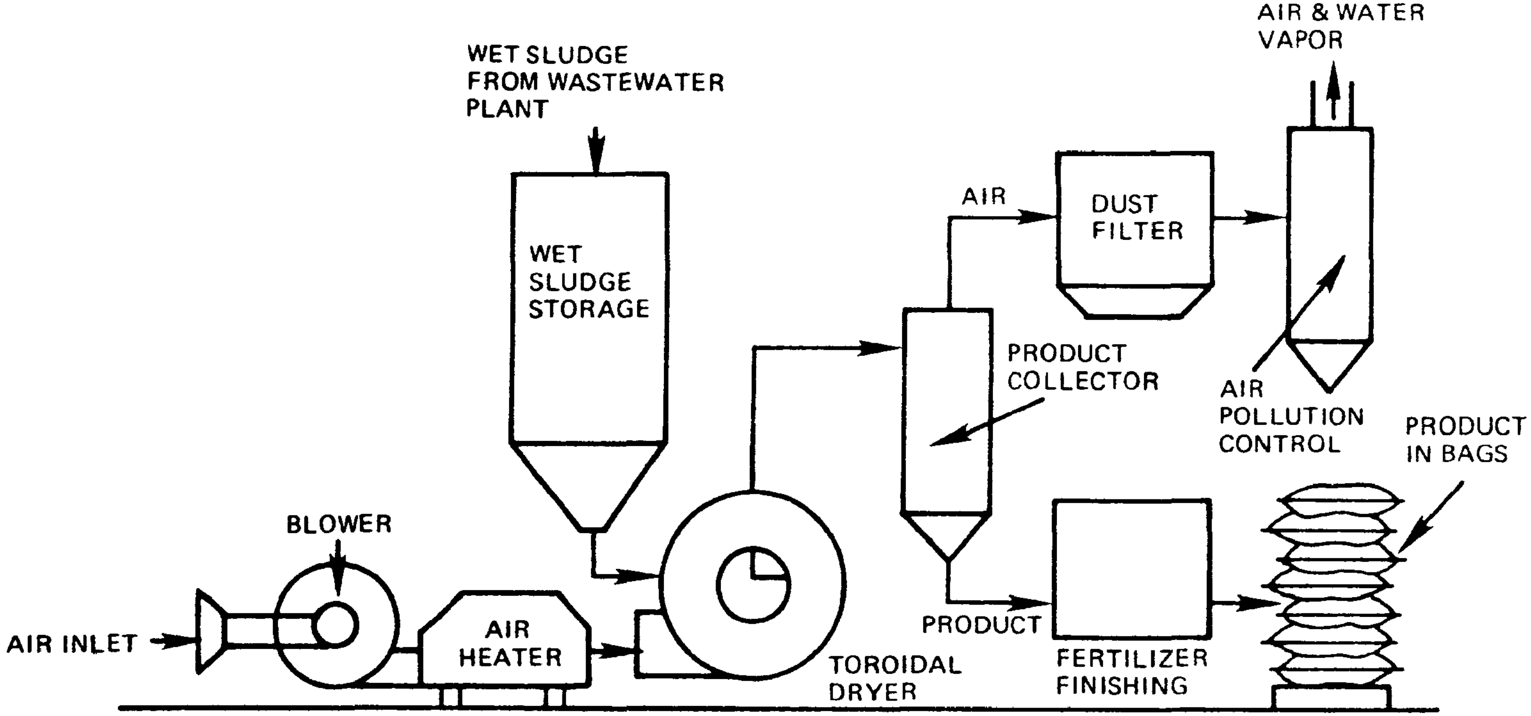


FIGURE 17. Sludge drying system using the jet mill principle[51] erosion of the drying unit has been encountered. In addition, the product has been extremely dusty, thereby limiting its marketability.

Capital cost data for the "Organo" system are unavailable at this time. The cost of operating the unit at Blue Plains has been as follows,[51] adjusting fuel oil costs to current levels of $0.50/gallon:

	Operating Costs Only Per Dry Ton
No. 2 Fuel Oil	$30.00
Electricity	9.08
Labor	6.81
Nitrogen Supplement	10.67
TOTAL	$56.56

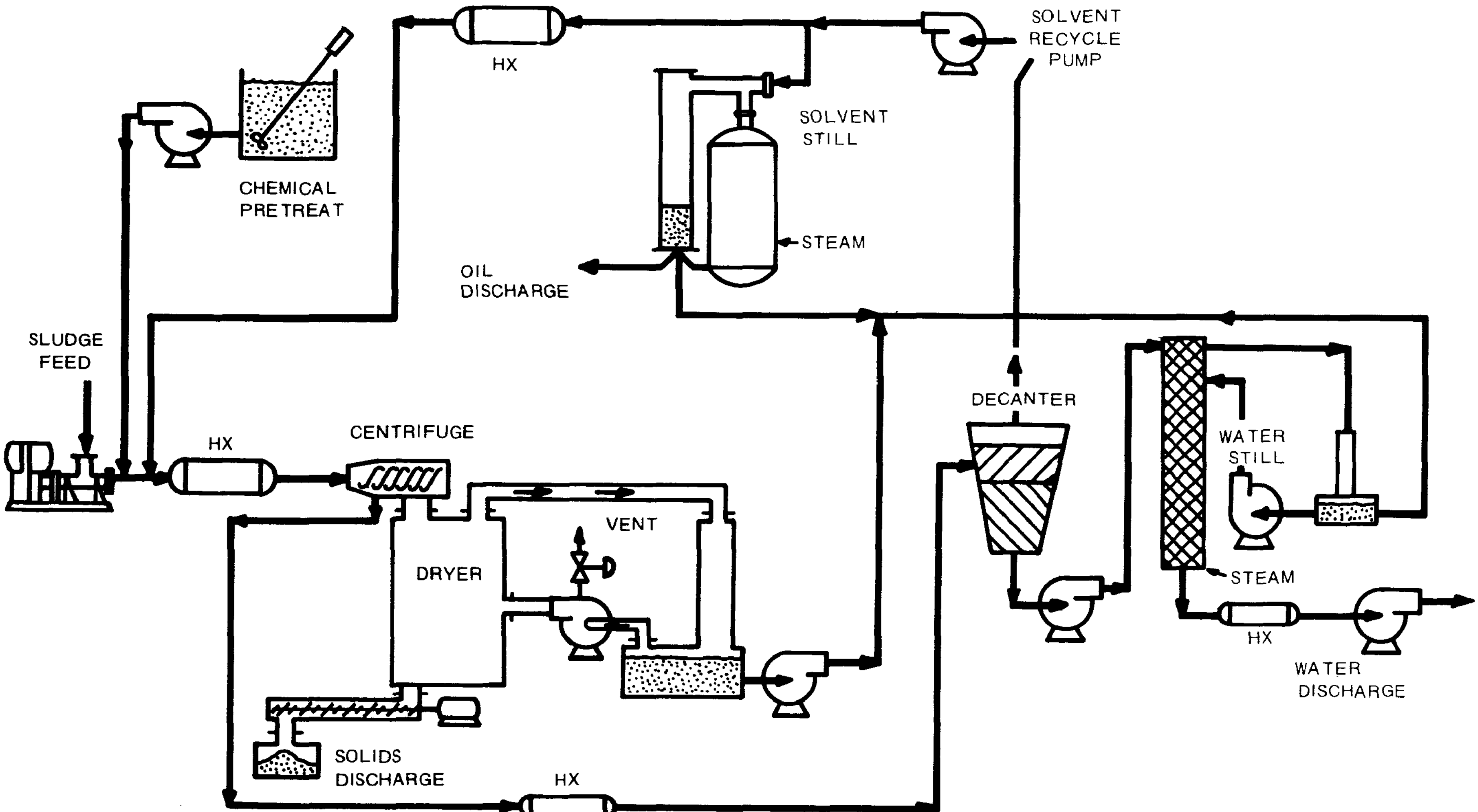
Unit costs for power, labor, and nitrogen were not reported[51] so these cost items may not be on a basis comparable to costs presented for other processes in this report.

Preliminary data from the Blue Plains plant indicate that with a feed sludge at 78 percent water, approximately 60 gallons of number 2 fuel oil (8,500,000 BTU) are required per ton of dry sludge processed (13 gallons per wet ton processed).

Solvent Extraction

A system (Basic Extractive Sludge Treatment of B.E.S.T.) for drying of sludge to 95% solids is under development by Resources Conservation Company[51,53-55].

In addition to drying the sludge, greases and oils are recovered for possible use as an energy source or commercial byproduct. Sludge is introduced into the B.E.S.T. system, stabilized at about 50°F and mixed with cold recycled solvent. The system uses triethylamine ("TEA") as the solvent in the primary dewatering step (See Figure 18). The solvent and water are completely miscible at temperatures below 65°F and are immiscible above that point. When the solvent and sludge are mixed below 65°F, the solids are easily separated by either centrifuge or a filter. Because the solvent-sludge mixture is warmed to about 60°F by the addition of heat of solution, it is chilled to 50°F before being fed to a solid bowl centrifuge. After the centrifuge separates the solvent-water-solids mixture, solids go to a dryer and the liquid fraction to a decanter. The closed-cycle dryer removes solvent and produces dry solids (95% solids, sterile); the solvent driven off is condensed and returned to the system. The water-solvent fraction is heated and moved to a decanter where the solvent and water form two layers. This solvent is recycled to the system, and the water layer is fed to a steam stripping distillation column where the remaining fraction of solvent is recovered and returned to the system. The sterile dry solids produced by this process can be used as a fertilizer, a soil conditioner, or as a raw material depending upon the composition of the original sludge.



NOTE: HX = Heat Exchange

Figure 18
B.E.S.T. System Schematic

Heat and electricity requirements are a function of the solids fed and may be summarized as follows:

% Solids in Feed	Kwh/lb Solids Feed	BTU/lb Solids Feed
7	0.52	3,514
11	0.38	3,266
20	0.26	3,088

For a typical sludge containing 16% oil, about, 2,000 BTU will be recovered in the form of oil per pound of dry solids. The recycle stream from a primary-WAS mixture is expected to have the following quality:

BOD = 2760 mg/l   COD = 7335 mg/l   SS = 400 mg/l

The estimated costs for the B.E.S.T. process for a primary-WAS mixture centrifuged to 11% solids are shown in Table 17 (based upon data from manufacturer gathered in pilot scale tests - yet to be confirmed on plant scale). If a potential value of $40/ton for the recovered fertilizer could be achieved, it is apparent that the costs would be very attractive.

DISPOSAL AND LAND APPLICATION

The three major alternative modes for application of sludge to the land and their constraints have been defined[4] as:

Disposal	Principal Sludge Form	Main Constraints
Sanitary Landfill	Dewatered cake or ash	Gas, leachate, and runoff control; land availability.
Sites Dedicated to Sludge Disposal	Liquid or Dewatered	Leachate, runoff control, land availability.
Cropland Application	Liquid, cake dried, or compost.	Application rate, unsatisfactory sludge.
Land Reclamation	Liquid or Dewatered	Application rate, unsatisfactory sludge, availability of land.

EPA has recently published a Technical Bulletin on Sludge Disposal Methods[62] for public review and comment which state that: "Because land application of sludge conserves organic matter, nitrogen, phosphorus, and certain essential trace elements, such utilization is encouraged when it is supported by environmental assessment and, if necessary, an

TABLE 17

ESTIMATED COSTS OF DRYING BY
SOLVENT EXTRACTION (B.E.S.T. PROCESS)
FOR PRIMARY + WAS AT 11% SOLIDS

ITEM	10 TON/ DAY	25 TON/ DAY	50 TON/ DAY	100 TON/ DAY
Amortized Capital (x 0.0944)	$38.80	$28.97	$22.76	$18.88
Electric ($0.025/KWH)	19.00	19.00	19.00	19.00
Fuel ($3.00/MBTU)	19.60	19.60	19.60	19.60
Maintenance	12.33	9.21	7.23	6.00
Operations	8.63	4.60	3.45	2.30
Solvent (TEA at $0.89/lb)	2.78	2.78	2.78	2.78
Lime	2.10	2.10	2.10	2.10
Recycle Stream Treatment	4.06	3.68	3.44	3.34
Subtotal	$107.30	$89.94	$80.36	$74.00
Fuel Credit(Recovered Oil)	(12.30)	(12.30)	(12.30)	(12.30)
TOTAL	$95.00	$77.64	$68.06	$61.70

environmental impact statement".

"Specifically, stabilization of sludge and subsequent land application for enhancement of parks and forests and reclamation of poor or damaged terrain should be considered for the utilization of sludge. Application of stabilized sludge to agricultural lands on which crops entering the human food chain will not be grown may also be regarded as an environmentally acceptable method of sludge disposal. However, application of sludge to lands on which crops entering the human food chain will or may be grown must be examined closely in terms of protection of human health and future land productivity. Priority consideration should be given to non-agricultural uses".

The draft Bulletin does not yet represent EPA policy as it may be revised as a result of the public review process.

Sanitary Landfill

The draft Bulletin[62] states, "Sanitary landfill of sludge, either separately or along with municipal solid waste, is acceptable when supported by the environmental assessment and, if necessary, an environmental impact statement".

The Bulletin also states that the landfill must be designed and operated in accordance with EPA Guidelines for Land Disposal of Solid Wastes (40 CFR 241 Appendix III); that the sludge must be stabilized prior to landfill; and that daily soil cover must be provided.

A survey of 176 landfill operations in 1972 found that only 30% permitted disposal of sewage sludge[65]. Despite this rather low percentage, stabilized sludge in landfills is recognized as an acceptable method of disposal[4,62]. EPA estimates[1] that 40% of wastewater sludged are disposed of in landfills and dumps currently and it was projected that this percentage will be maintained in 1985.

The landfill site's geology, hydrology, and soil conditions should be considered relative to the need for adequate protection of groundwater, conformation of area land use planning, and provision of an adequate quantity of earth cover[4].

Adequate monitoring of the landfill site is essential[62]. The monitoring plan must be specifically designed for applicable local conditions and should include monitoring groundwater observation wells, surface water, sludge and soils for heavy metals, persistent organics, pathogens, and nitrates. Leachate and runoff from a sanitary landfill should be minimized and when necessary collected and suitably treated to prevent pollution of ground and surface waters.

Although past practice has emphasized disposal of ash or dewatered (i.e., 20% solids) sludge, a recent study[64] indicates that liquid digested sludge (4% solids) can be successfully disposed of in a landfill.

With use of proper sludge spreading techniques, the municipal solid waste had sufficient absorptive capability to retain the associated sludge moisture and prevent leachate generation. The entire liquid sludge production from Oceanside, Calif. has been disposed of in a landfill since 1972.

The costs for landfill of sludge are reported to be $1-5/ton[4,64] at the landfill site. Transportation costs are discussed separately in a later section of this paper. Total costs at Oceanside for truck transport, unloading, and landfill disposal of liquid (4% solids) sewage sludge was $25-32/ton - economically competitive with other alternatives there.

Of course, landfilling is a disposal technique which makes no use of the nutrients in the sludge. The following section discusses land application which does reuse these nutrients.

Cropland Application

It would be impossible in this brief paper to completely address the factors involved in land application of sludges and to review past experiences. Literally hundreds of references are available on the topic - many of which are listed in references 69 and 75. Current practices and much information is contained in two seminar proceedings[72,73]. Design guidance is also presented in reference 6. Major cities such as Denver[66] and Chicago[68] are applying their sludge to the land now. San Francisco[67] is initiating a study of such a plan. There are numerous, successful land application systems utilizing liquid or dewatered sludge throughout the U.S. which accounted for disposal of 20 percent of the sludges in 1972[1]. EPA projects the percentage will increase to 25% in 1985[1].

Prior to applying sludge to the land, sludge stabilization is required to avoid nuisance conditions and minimize health hazards. Digestion (anaerobic or aerobic) is the most commonly used stabilization technique and is discussed in detail in the next section of this paper.

Typically, the land application site is remote from the plant site. The sludge may be transported by truck, barge, railroad or pipeline as discussed in detail in a subsequent portion of this paper. Transport costs may comprise a very significant portion of the overall costs of land application.

Storage of sludge between treatment and land application is usually required because the application rate of the sludge to the land is usually not the same as the rate at which sludge is generated. Treated sludge will be generated at nearly a constant rate; whereas, the sludge disposal rate will depend on weather conditions, field conditions, and the application method.

The critical factor for determining the volume of the storage facility is the length of time the disposal area cannot be used. The influences of the method of application, the climatic conditions, and the site may require very small storage volume or storage for several months. For example, in Shreveport, Louisiana, it was determined that 150 day storage would be necessary[71]. Rainfall data, by days, for the past 10 years were reviewed and the operation of land disposal was synthesized upon this period. By methods similar to a mass hydrograph analysis, a maximum storage period of 150 days were derived.

Where storage requirements are minimal, a second stage anaerobic digester may be used for storage. A covered digester is well suited for sludge storage because it will contain odorous gases which may be a problem in open basins or lagoons.

There are two philosophies concerning land application operations: (1) apply the sludge to a plot of land which will be used for growing agricultural products or other vegetation (parkland, forests, etc.), (2) to dedicate the area to the disposal of sludge with no attempt to grow crops. Overall management of a system using sludge for crop growth is more complex because the needs of the crop must be carefully balanced against sludge disposal considerations.

The advantage of an agricultural operation in conjunction with sludge disposal is the beneficial use of nutrients in the sludge and the removal of nitrogen, heavy metals, etc., from the soil. It has been estimated[70] that some 480,000 tons of phosphorus could be recycled if land application were practiced for all sludges when secondary treatment is applied to all U.S. wastewaters. The EPA Bulletin[62] recognizes this advantage but also expresses a concern over possible human food chain effects:

> "Although utilization of sewage sludges as a resource to recover nutrients and other benefits has been encouraged by PL 92-500 and the EPA Science Advisory Board, the workgroup members and others involved in developing this Technical Bulletin have received conflicting opinions concerning the overall merits vs hazards of applying sludges to cropland. Possible adverse effects upon the human food chain (e.g., potential for increasing human cadmium intake) has remained a major concern expressed whenever this practice is considered. The relative risks of applying sewage sludges to croplands, when compared to other routes through which these contaminants enter the human diet, have yet to be determined".

Sludge constituents such as viruses, organics, cysts, and parasites are of concern from the standpoint of their ultimate fate and effect on the environment. However, they do not usually limit the rate at which sludge is applied to the land. Those constituents of sludge which potentially may limit the application rate of the sludge to the land are the amount of water in the sludge, the amount of nitrogen in the sludge, and the quantity of heavy metals in the sludge.

If surface runoff is to be prevented, the application of water to land obviously cannot exceed the amount of water lost by percolation, evaporation, and transpiration. While not of concern with dewatered sludges, many systems apply liquid sludge to the land. The amount of water which may be applied will vary depending on the climatic conditions, the type of soil, whether vegetation grows on the disposal site, and the type of vegetation which may be grown on the disposal site. Although the water application rate to the land should be considered, for sludges having a dry solids content of greater than 2 percent, water content usually does not limit the rate at which sludge may be applied to the land. For example, a 2 percent sludge applied at a liquid application rate of 1 inch per week will result in a solids loading of 120 tons per year per acre. At this application rate, normally some other constituent (such as nitrogen) in the sludge will control the application rate.

If nitrogen pollution of the groundwater is a concern, the amount of nitrogen in the sludge may limit the annual sludge application rate. The nitrogen concentration of sewage sludges should be measured for each sludge. For an anaerobically digested raw sludge, the total nitrogen is typically 50 to 70 pounds of nitrogen per ton of dry sludge solids. The amount of nitrogen (as N) found in waste activated sludges or aerobically digested sludges is generally higher than that of raw or anaerobically digested sludges and typically ranges from 100 to 120 pounds of nitrogen per ton of the dry weight sludge solids.

The amount of nitrogen contained in the sludge is a concern because of the potential for nitrogen to leach to the ground water in the form of nitrate. The concentration of nitrate is limited in potable water supplies to 10 mg/l (as N). The fate of nitrogen in soils and in ground water is difficult to predict with accuracy because of the many processes which can affect the fate of nitrogen in the soil system. There is no doubt that excessive applications of nitrogen will lead to passage of nitrogen into the ground water. High nitrate contents are observed in Illinois and Washington in ground waters below agricultural areas utilizing commercial fertilizers. To avoid nitrate pollution of the ground waters, a balance between nitrogen applied in the sludge and that removed in the crop or by other mechanisms must be struck.

In a single growing season, crop uptake of nitrogen may vary from 50 to 600 lbs/acre/yr depending upon the specific crop growth. Typical ranges are (lbs/acre/yr): forest crops - 20-60; field crops - 50-150; forage crops - 75-600. Consideration of the nitrogen balance may reduce the permissable sludge loading rate from values of 100 dry tons per acre per year experienced in average conditions without concern for a nitrogen balance to as low as 5 tons per acre per year. The Chicago, Illinois "Prairie Plan" proposes initial application rates of 75 dry tons per acre per year to previously strip-mined land, which will taper to 20 tons of dry sludge per acre per year and an associated 1,000 pounds of nitrogen per acre per year (50 lbs N/dry ton). The sludge application rate for the northeast water pollution control plant at the City of Philadelphia, Pennsylvania, may be limited to 25 dry tons per acre per year in order to prevent nitrate-nitrogen leaching to the ground water in excess of 10 mg/l[71]. Added discussion of nitrogen balances in crop systems is presented in documents on wastewater application to the land but is applicable to sludge systems as well[74,76,77].

The third constituent of sewage sludge which may affect the application rate of sludge to land is the heavy metals content. Elements in sludge that are potential hazards to plants or the food chain are: B, Cd, Co, Cr, Cu, Hg, Ni, Pb, and Zn. The quantity of heavy metals in sewage sludge is highly variable and depends to a great extent on the types of industry connnected to the sewage collection system and the degree of emphasis and enforcement to which the operating agency imposes on limiting the heavy metals which enter the sewage collection system. Table 18 presents heavy metals concentrations for several sludges.

Among the factors that affect the toxicity of metals to plants are:

- The amount of toxic metals present in the soil.

- The toxic metals present. Diffent metals differ in their toxicity to specific plants and in specific soils.

- The pH of the amended soil. The toxic metal content safe at pH 7 can easily be lethal to most crops at pH 5.5. Land application may lead to a lowering of the soil pH due to nitrification of the NH_4-N added. Properly selected soil amendments can readily be used to overcome this potential problem.

- The organic content of the amended soil. Organic matter chelates the toxic metals and makes them less available to injure plants.

- The phosphate content of the amended soil. Phosphate is well known for reducing Zn availability to plants and decreasing the stunting injury caused by excessive levels of toxic metals.

- The cation exchange capacity (C.E.C.). The C.E.C. of the soil is important in binding all cations, including the toxic metal cations. A soil with high C.E.C. is inherently safer for disposal of sludge than a soil with low C.E.C.

- The plant grown on sludge treated soil. Plant species vary widely in tolerance to heavy metals, and varieties within a species can vary three to tenfold.

A recent EPA report[88] presents a detailed review of the potential hazards associated with specific heavy metals. The report concludes that, with correct management practices, manganese, iron, aluminum, chromium, arsenic, selenium, antimony, lead, and mercury pose relatively little hazard to crop production and plant accumulation when sludge is applied to soil. Cadmium, copper, molybdenum, nickel, and zinc can accumulate in plants and may pose a hazard to plants, animals, or humans under certain circumstances.

TABLE 18

HEAVY METALS CONTENT OF SEWAGE SLUDGES[86]
(mg/kg, ppm)

	Range	Mean	Median
Ag, Silver	nd - 960	225	90
As, Arsenic	10 - 50	9	8
B, Boron	200 - 1430	430	350
Ba, Barium	nd - 3000	1460	1300
Be, Beryllium	nd	nd	nd
Cd, Cadmium	nd - 1100	87	20
Co, Cobalt	nd - 800	350	100
Cr, Chromium	22 - 30,000	1800	600
Cu, Copper	45 - 16,030	1250	700
Hg, Mercury	0.1 - 89	7	4
Mn, Manganese	100 - 8800	1190	400
Ni, Nickel	nd - 2800	410	100
Pb, Lead	80 - 26,000	1940	600
Sr, Strontium	nd - 2230	440	150
Se, Selenium	10 - 180	26	20
V, Vanadium	nd - 2100	510	400
Zn, Zinc	51 - 28,360	3483	1800

Cadmium is a nonessential element which can be a serious hazard to animals and humans if dietary levels are increased substantially. Cadmiums lability in soil is reduced by organic matter, clay, hydrous iron oxides, high pH, and reducing conditions. Annual cadmium application rates, soil pH, and crop species and varieties have a major influence on the cadmium concentration in plant tissue. One study[78] found that 35 years of sludge application resulted in large accumulations of Cd and other trace elements in the soil but no significant accumulation in the grain of corn plants. Concentrations in the leaves and roots were significantly higher than normal. The following management options are available to limit cadmium accumulation in the food supply to a relatively low level on sludge-treated land: (1) maintain soil pH at or above 6.5; (2) grow crops which tend to exclude cadmium from the whole plant or from reproductive tissue; (3) apply low annual rates of cadmium, and use sludges which have a low cadmium concentration; and (4) grow nonedible crops.

Copper, although essential to plants, can become toxic to them at high concentrations. Sludges often contain appreciable levels of copper, but application of sludge to soil results in only slight to moderate increases in the copper content of plants. Under good management practices, copper in sludges will seldom be toxic to plants and should not present a hazard to the food supply.

Molybdenum is not particularly toxic to plants, even when applied at relatively high levels. As a result, molybdenum may accumulate in plants at concentrations sufficient to cause molybdenosis in ruminant animals without prior warning from plant behavior. The practice of maintaining the soil pH at 6.5 or higher results in greater solubility and availability of the molybdenum than would occur at lower pH values. However, since sludges are usually very low in molybdenum, it is doubtful that molybdenum in sludge would present a serious hazard to the health of grasing animals except for the unusual circumstances in which forages from sites receiving high-molybdenum sludge form the major part of the animal diet.

Sludges often contain substantial quantities of nickel, which appears to be more readily available from sludges than from inorganic sources. Nevertheless, toxicity of nickel to plants occurs only on acid soils. If the soil pH is maintained at 6.5 or above, nickel should not cause toxicity to plants or pose a threat to the food supply.

Zinc, an essential element for both plants and animals, is often found in sludge at relatively high concentrations. Additions of sludge to soil may cause substantial increases in the zinc content of plants, but toxicity seldom occurs. In general, if the pH of sludge-treated soils is maintained at 6.5 or greater, zinc should not be a hazard to plants or to the food supply unless exceptionally high amounts are added in the sludge.

Heavy metal concentrations may restrict application of sludges in the New York-New Jersey Metropolitan Area to 2 dry tons/acre/year[60].

Sludge may be applied to the land in a variety of ways. Small plants may spread liquid sludge directly form tank trunks. In some cases, shallow trenches may be dug, filled with sludge, and covered. Sludge may also be applied through sprinkler systems using large diameter spray nozzle openings in cases where aerosol transport can be controlled by adequate isolation of the site. In some cases, sludge has been injected into the subsoil under pressure. Ridge and furrow systems have also been used successfully. The method used is generally related to the quantity of sludge to be disposed and whether crops are to be grown on the site.

The proper management of the land application system is the key to the success of the system. The economical and technical success of the project depends on intelligent decisions, firm and established project goals and proper monitoring of results. Monitoring of ground water and leachate (percolate) is information necessary to assure protection of the ground water. Where crops are grown, close cooperation between the treatment system management and farming operation is required. Scheduling of sludge application with farm operations such as planting, tilling, spraying and harvesting is vital to successful management.

It is difficult to generalize on the cost of land disposal of sludges because of the tremendous number of variables which affect cost such as land costs, climate, soil types, distance to disposal area from treatment plant site, allowable loading rates (may range from 2-100 dry tons/acre/year) Chicago was experiencing costs of $70+ per dry ton in 1972 with a lengthy barge haul involved(68). Of this total, about $20/ton was related to the land application portion of the project with the remainder resulting from digestion, concentration, and transport. If the barging operation were replaced by a pipeline, total costs were projected to drop to $35/ton. Past reports of costs(11) at other projects range from $8 to $50/ton. A recent report(51) estimated the costs for several alternative land application approaches for a large city for sites 20-100 miles from the treatment plant. Estimated costs were $39-$57/ton including, in some cases, dewatering to 20% solids. Transport costs, as discussed in a later section, are often the major cost item in a land application system. Costs for the New York Metropolitan Area(60) were estimated at $110-$185/ton but were adversely affected by long transport distance (100 miles), low application rates (5-10 tons/acre/year), and high land costs ($6000/acre). Where adverse factors such as these exist, land application may not be cost effective. However, there are many municipalities where conditions are such that land application is cost effective.

STABILIZATION

The principal purpose of sludge stabilization are to render the sludge less putrescible, to reduce the pathogenic content, and to reduce the sludge quantity. Processes commonly used are: anaerobic and aerobic digestion and composting.

Anaerobic Digestion

In this process, the organic matter in the sludge is stabilized in an anaerobic environment (oxygen devoid). Most modern systems are "high-rate" systems utilizing one or two stages (see reference 79 for detailed information on the process). A typical two-stage process is shown in Figure 19. The stabilization of the sludge occurs in the first stage, mixed and heated unit with the second stage digester providing settling and thickening. In a single stage system, the secondary digester is replaced by some other thickening process. The digester is heated to 85-95^{o}F and typically provides 15 days or less detention of the sludge.

The process has been successful when primary sludge or combinations of primary sludge and limited amounts of secondary sludge constitute the system's feed. With the advent of wastewater treatment systems that are more efficient than simple sedimentation, large quantities of activated sludges are produced at the plants. This additional sludge, when placed in a two-stage anaerobic digestion process, can cause high operating costs and poor plant efficiencies. The basic cause of the problem is that the additional solids do not readily settle or dewater after digestion.

The process converts about 50% of the organic solids to liquid and gaseous forms - providing a substantial reduction in the quantity of sludge requiring disposal. A major component of the gaseous by-products (usually about two-thirds) is methane. The resulting gas has a typical heat value of 600 BTU/scf with about 15 scf of gas formed per pound of volatile solids destroyed.

The use of anaerobic digester gas has been practiced to some extent in wastewater treatment plants for many years. Digester gas is currently being used at several wastewater treatment plants to heat digesters and buildings and as fuel for engines that drive pumps, air blowers and electrical generators.

The following criteria give estimates for gas and heat available from anaerobic digestion[38]:

	Primary Sludge	Waste Activated Sludge	Total
Gas Produced, scf per million gallons treated.	5,175	5,670	10,845
Heat Available, Btu per million gallons treated.	3,105,000	3,402,000	6,507,000

A schematic of a typical system to utilize digester gas in an internal combustion (IC) engine is shown in Figure 20. As indicated in this figure the engine could be coupled to a generator, blower or pump. Typical IC engine efficiency is 36.4% (7,000 BTU/hp-hr). An IC engine-generator typical efficiency is 30% (11,400 BTU/hp-hr). The electrical energy

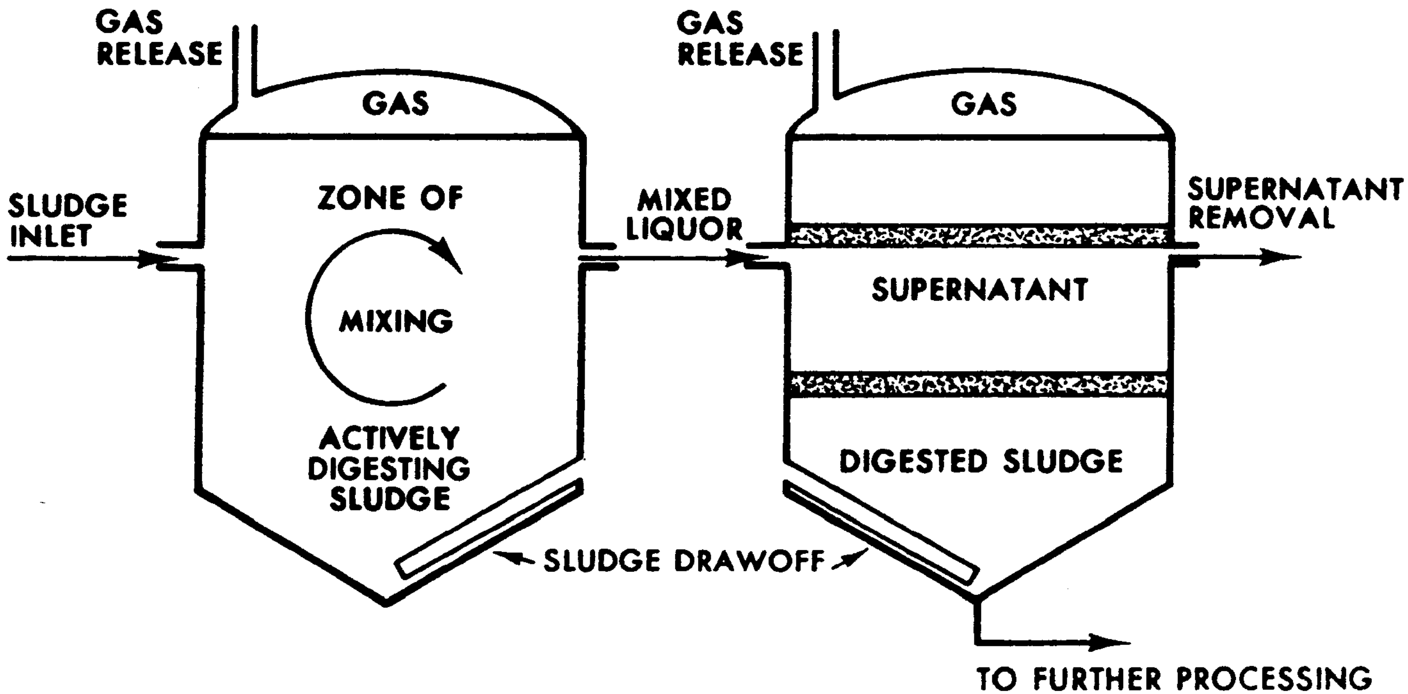


FIGURE 19. Two-stage anaerobic digestion.

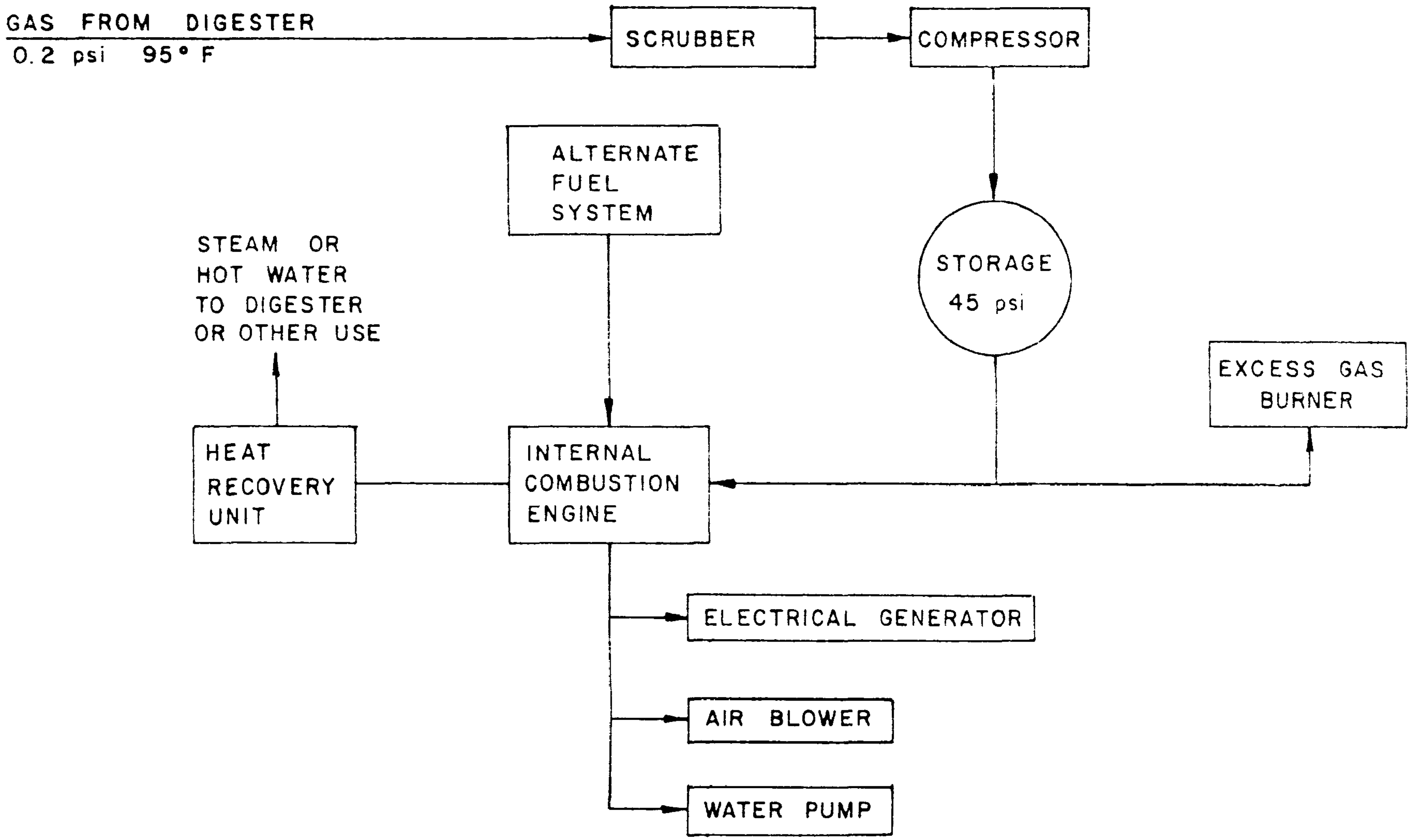


FIGURE 20. ANAEROBIC DIGESTER GAS UTILIZATION SYSTEM[38]

which can be generated from anaerobic digestion of primary and WAS could supply about 85% of the electrical energy required for an activated sludge plant while also providing over 50% of the heat for the digestion process itself[38].

The process also provides substantial reductions of pathogenic bacteria (85-100%)[4].

The process disadvantages include: (1) process control requires considerable operator expertise and time to achieve optimum solids reductions and gas production (2) the supernatants from the process are often high in BOD, solids, and ammonia and impose an added load when recycled to the wastewater treatment system.

Updating previously published costs[32] for two-stage anaerobic digestion to the same basis used for other processes in this report results in the following costs per dry ton:

	Tons Per Day Dry Solids to Digester			
Sludge Source	10	25	50	100
Primary	$18.80	$15.50	$14.30	$13.70
Primary + WAS	$46.80	$42.70	$42.30	$40.80

No credit for the fuel value of the digester gas is reflected in the above estimates. At $3/M BTU, the value of the fuel could be $16/ton of dry solids for primary sludge digestion and $18.60/ton for primary + WAS.

Aerobic Digestion

Aerobic digestion consists of separate aeration of waste primary sludge, waste biological sludge, or a combination of waste primary and biological sludges in an open tank. It is usually used to stabilize excess activated sludges or the excess sludges from small plants which do not have separate primary clarification. Figure 21 is a schematic diagram of an aerobic digestion system. The advantages that the system offers over anaerobic digestion include: simpler operation, less capital cost, and better supernatant quality. Disadvantages are: higher operating cost, poor sludge dewatering characteristics, and net energy consumption rather than energy production.

Current practice is to provide 10-15 days of detention time for the stabilization of excess biological sludges, additional time is required when primary sludge is included[4].

The destruction of solids is a function of temperature (the process is not heated). Volatile solids reductions of 35-50% have been achieved. Pure oxygen rather than air can be used in the digester to enable higher loading rates. The oxygen system also has the advantage of generating heat from the biological reaction which increases the sludge temperature and a corresponding increase in the rate of solids destruction.

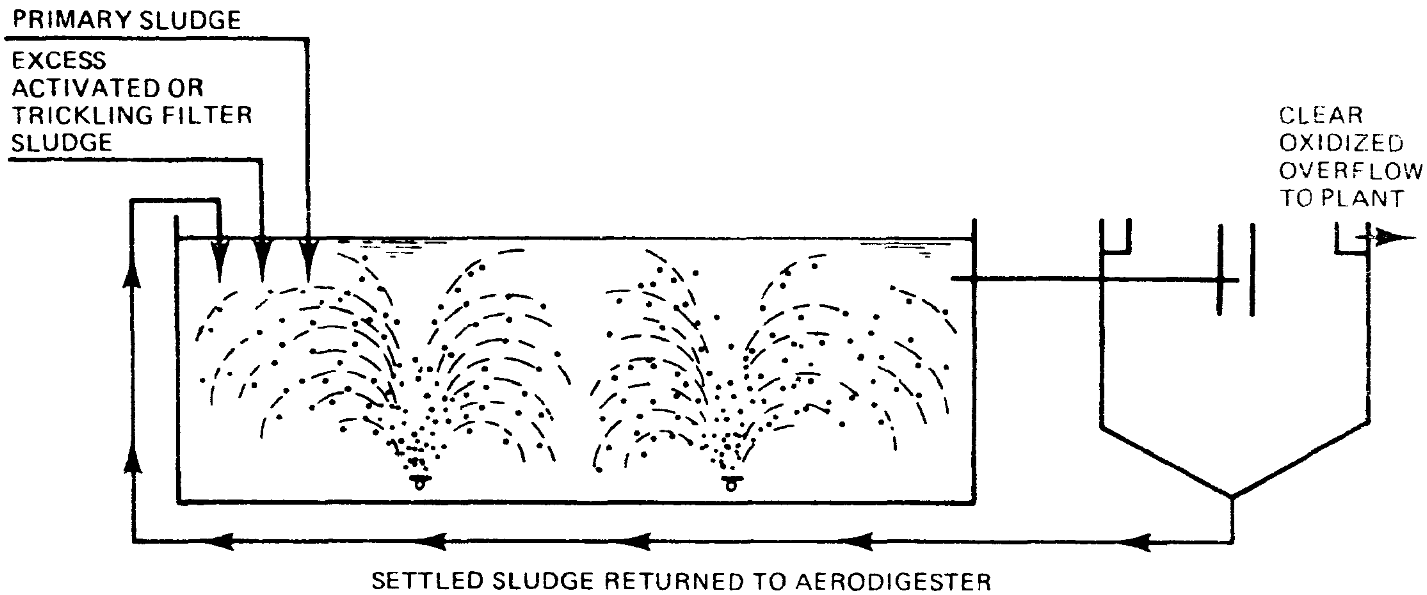


FIGURE 21. AEROBIC DIGESTION SYSTEM[4]

Based upon criteria presented recently[80], Table 19 presents costs calculated for the aerobic digestion process for primary + WAS (exclusive of solids separation an/or thickening). Capital costs are significantly less than for two-stage anaerobic digestion partly because total sludge detention time is about one-third that of two-stage anaerobic digestion. O & M costs are significantly higher for the aerobic process due to power consumption. In order to properly compare these two systems, differences in thickening, dewatering and supernatant treatment costs must be added to each of the digestion system costs.

Composting

Composting is a method of biological oxidation of organic matter in sludge by thermophilic organisms. Composting, properly carried out, will dewater, destroy objectionable odor producing elements of sludge, destroy or reduce disease organisms because of elevated temperature, and produce an aesthetic and useful organic product.

Composting of wastewater sludge differs significantly from processing and composting of solid waste; therefore, past poor publicity related to composting of solid waste need not discourage the use of composting in processing of wastewater sludge. There are many differences between the two[56]:

- Composting of solid waste is proceeded by complex materials handling and separation process.

- Solid waste varies widely in composition which makes processing more difficult.

- Many past solid waste composting operations were operated and evaluated on the basis of profit making potential rather than as an alternative disposal means.

- For a given population, the volume of solid waste compost is several times the volume of wastewater sludge compost, therefore, solid waste creates a much greater marketing or disposal task.

Composting systems generally fall into three categories: (a) pile, (b) windrow, and (c) mechanized or enclosed systems. The pile (static aerated pile) and windrow systems have been used almost exclusively in composting sewage sludge because of their low cost and demonstrated performance. In general, the windrow process has been used in composting digested primary and waste activated sludge in various combinations. The static pile method has been used more recently for composting raw primary and waste activated sludge in various combinations. The windrow process was found to be unsuitable for composting raw sludge because of odor problems. Thus, at this time, the windrow process has been demonstrated on digested sludges, the static pile method on raw sludges, and mechanized or enclosed systems have not been used to any extent recently

TABLE 19

AEROBIC DIGESTION COSTS

UTILIZING CONVENTIONAL AIR SYSTEM

Item	Tons Per Day of Dry Solids (Primary + WAS)			
	10	25	50	100
Construction Cost	$800,000	$1,400,000	$2,200,000	$3,300,000
Engr., Legal, Adm., & During Construction (19%)	152,000	266,000	418,000	627,000
Total Capital Cost	$952,000	$1,666,000	$2,618,000	$3,927,000
O & M Labor @ $10/Hr.	32,000	50,000	80,000	105,000
Power @ $0.025/Kwh	37,500	75,000	150,000	300,000
Maintenance Materials	7,000	10,000	16,000	20,000
Annual O & M Costs	76,500	135,000	246,000	425,000
Annual Capital Cost (x .0944)	90,000	157,000	247,000	371,000
Total Annual Cost	$166,500	$292,000	$493,000	$796,000
Cost Per Ton of Dry Solids	$45.61	$32.00	$27.00	$21.80

in the U.S. on sewage sludge. Thus, only windrow and static pile processes will be discussed in detail.

The general composting method is very similar for both processes. The dewatered sludge (typically 20 percent solids) is delivered to the site and is usually mixed with a bulking agent. The purpose of the bulking agent is to increase the porosity of the sludge to assure aerobic conditions during composting. If the composting material is too dense or wet it may become anaerobic thus producing odors or if it is too porous the temperature of the material will remain low. Low temperatures will delay the completion of composting and reduce the kill of disease organisms.

Various bulking materials can be used and suitable low cost materials include wood chips, bark chips, rice hulls, and cubed solid waste. Unscreened finished compost has also been used. Generally, one part sludge (20% solids) is mixed with three parts bulking agent although this mixture can be varied depending on moisture content of sludge, type of bulking agent, and local conditions. The sludge-bulking agent mixture is then formed into the windrow or static pile as applicable.

Following composting, the product is removed from the windrow or static pile and cured in storage piles for 30 days or longer. This curing provides for further stabilization and pathogen destruction. Prior to or following curing, the compost may be screened to remove a portion of the bulking agent for reuse or for applications requiring a finer product. The compost can also be used without screening. Removal of the bulking agent also reduces the dilution of the nutrient value of the compost.

The compost is then ready for distribution.

Windrow Composting - The sludge-bulking agent mixture, (2-3 parts of bulking agent by volume to one part of sludge) is spread in windrows with a triangular cross section. The windrows are normally 10 to 16 feet wide and 3 to 5 feet high. An alternative method of mixing the bulking agent and sludge and forming the windrow consists of laying the bulking agent out as a base for the windrow. The sludge is dumped on top of the bulking agent and spread. A composting machine (similar to a large rototiller) then mixes the sludge and bulking agent and forms the mixture into a windrow. Several turnings (about 8 to 10 times) are necessary to adequately blend the two materials.

The windrow is normally turned daily using the composter; however, during rainy periods turning is suspended until the windrow surface layers dry out. Temperatures in the windrow interior under proper composting conditions range from 55 to 65°C. Turning moves the surface material to the center of the windrow for exposure to higher temperatures. The higher temperatures are needed for pasteurization and kill of most pathogenic agents. Turning also aids in drying and increases the porosity for greater air movement and distribution.

The windrows are turned for a two week period or longer depending on the weather and efficiency of composting. The compost windrow is then flattened for further drying. The compost is moved to curing when the moisture content has decreased to approximately 30 to 40 percent. Proper windrow composting should produce a relatively stable product with a moisture content of 30 to 40 percent which has been exposed to temperatures of at least 50°C for a portion of time during the composting process.

The composting process requires longer detention times in cold or wet weather, therefore, climate is a significant factor with the windrow process in open spaces. Covering the composting area would significantly reduce the effects of cold weather and nearly eliminate the problems of wet weather. In any case, the curing area should be covered if operations are to be carried out during precipitation.

Static Pile Composting - The static pile composting method[57,58] as applied to raw sludge requires a forced ventilation system for control of the process. The pile then remains fixed, as opposed to the constant turning of the windrow, and the forced ventilation system maintains aerobic conditions.

A base is prepared for the pile consisting of a 1 foot thick layer of bulking agent or previously composted unscreened product. A 4-inch diameter perforated pipe is installed in the base as an aeration header. The base in constructed with a typical plan dimension of approximately 40 by 20 feet. The sludge-bulking agent mixture is piled on this base to a heighth of approximately 8 feet to form a triangular cross section. The pile is capped with a 1 foot layer of screened compost product. This top layer extends down the sides to help absorb odors and to act as a shield or roof against penetration of precipitation. A typical static pile is illustrated in Figure 22. An alternative configuration is the extended static pile method where subsequent piles are "added" to the initial static pile. This configuration saves space compared to a number of separate static piles.

The perforated underdrain pipe is attached to a blower by pipe and fittings. The other side of the blower is piped to a smaller, adjacent pile of screened compost product. Air and gases are drawn by the blower from the static compost pile and discharged through the small pile of product compost. The small pile effectively absorbs odors. The operating cycle of the blower is adjusted to maintain oxygen levels in the exhausted gases and compost pile within a range of 5 to 15 percent. Temperatures within the compost pile will vary somewhat with monitoring location in the pile, but should reach 60-65°C. Normally the blower is operated on an on-off cycle to maintain proper oxygen levels and temperatures within the pile.

After an average composting period of 3 weeks, the compost is moved to the curing area.

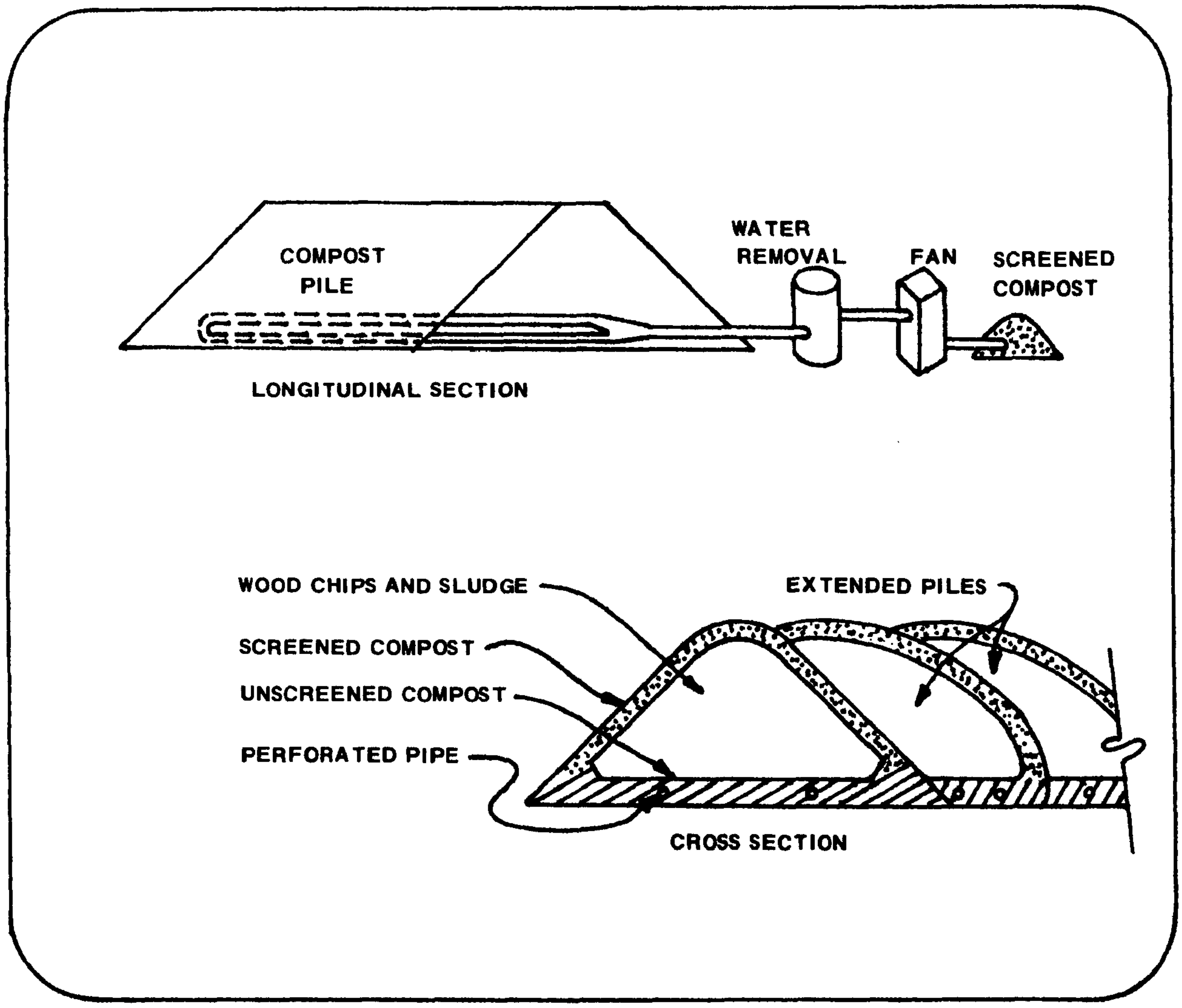


Figure 22

STATIC PILE COMPOSTING AS DEVELOPED BY THE AGRICULTURAL RESEARCH SERVICE AT BELTSVILLE, MARYLAND

Outdoor temperatures as low as -7°C and rain totaling 7 inches per week has not interferred with the successful outdoor operation of exposed static pile composting. Temperatures produced during static pile composting are generally above 55°C and often exceed 70 to 80°C.

The Product - The compost product has a slight musty odor, is moist, dark in color, and can be bagged. The texture of the compost varies depending upon the degree of screening. Compost is valuable as a soil conditioner and low grade fertilizer and varies widely in content. Typical compost contains an average of 1.5 percent nitrogen and 1.0 percent phosphorus. Agricultural Research Service Personnel indicate that proper static pile composting should reduce total and fecal coliform and salmonella below detectable limits. Compost produced by the windrow process is likely to contain detectable pathogens because lower temperatures are produced. Composting has little effect on total heavy metal content of the sludge, but there is some dilution and also some indication of a lower uptake rate after composting. Content and effect of heavy metals must be considered for each individual application.

The Economics - The economics of composting are determined by two factors; the cost of producing the compost and the cost of (or income from) disposal of the compost product.

The marketing of the end product is a key to the success of a composting effort. A recent market study(59) found several successful municipal sludge composting operations where all of the end product was sold or otherwise successfully used. The study concluded that the upper price limit for bulk sewage sludge compost would be $4-$10/ton and for packaged, bagged, sewage sludge compost, $60/ton. Bagging costs could approach $30/ton.

Those municipal sludge compost marketing operations that have been successful have generally(59):

- had favorable local publicity.
- had the product available for pick-up (or make deliveries).
- offered guidelines for its use, or at least suggestions.
- offered the product at no cost or inexpensively.
- given the product a trade name.

The cost of producing compost includes the following elements:

- Amortization of land, capital site improvements, and structures.
- Amortization of major mobile equipment costs.
- Operation and maintenance costs.

Land requirements are affected by several factors but are typically 0.2-0.4 acres/dry ton for the static pile technique. Windrow techniques require 2-3 times more area.

The required site improvements and structures will vary depending on process used, availability of existing facilities, degree of mechanization of the process, and to a degree, the demands of the climatic region. Site improvements related to composting will generally include site access and improvements, bulking agent storage, bulking agent-sludge mixing area or mechanical fixed equipment, composting pads and appurtenances such as blowers, screening area, compost storage area, support facilities such as electrical, and fixed materials handling equipment.

Major mobile equipment includes screens, front loaders, trucks, and testing equipment. The number and size of major equipment will depend on the capacity and type of operation.

Operation and maintenance costs normally include:

- Labor for constructing the compost piles, handling materials, and screening the compost.

- Labor for regular inspection of operations and performing tests on the piles.

- Electrical energy for blowers, lighting, and other miscellaneous uses.

- O & M costs for the equipment including front loader and screen.

- Costs of transport of materials as required.

- Cost of bulking agent, typically $2 to $4 per cubic yard.

As compared to many other sludge handling processes, the amount of information available for estimating costs for sludge composting is rather limited, and the accuracy of estimates of costs is likely to be much less.

A study[60] of the sludge disposal alternatives for the New York-New Jersey Metropolitan area developed a cost of $40-45 per dry ton for composting large quantities of dewatered sludge without any hauling or land costs included.

The USDA and MES estimate the total cost for static pile composting of approximately 600 wet tons per day of sludge (20 percent solids) would be $20 to $40 per dry ton excluding land and hauling. Camp, Dresser, and McKee[61] estimated a cost of $45 per dry ton including land, but excluding hauling, to windrow compost 600 wet tons per day of sludge. They indicate that the cost would be less for static pile composting.

Preliminary studies indicate that total costs to a municipality for static pile composting should be in the range of $30 to $40 per dry ton of sewage sludge solids excluding dewatering and hauling, but including land at $10,000 per acre. This cost varies with local conditions and with the size of the operation. Windrow costs would be expected to be somewhat higher.

SECTION VI

SLUDGE TRANSPORT

It is becoming increasingly common to transport solids in liquid or dewatered form from one location to another as part of the treatment, disposal, or reuse steps. Significant technical and cost considerations must be evaluated in planning a transport system to achieve satisfactory results. The costs associated with transport can be very substantial.

This section will discuss general aspects of solids transportation systems by truck, barge, railroad, and pipeline.

A significant EPA sponsored sewage sludge transport cost study was completed by CWC[82]. The purpose of this study was to develop a method of calculating transport costs for each mode using basic parameters such as gallons of fuel, operator manhours, operating miles, and similar factors. Therefore, the information developed in the study would not grow out of date with inflation and current unit costs could be used in making calculations at any future date. Formats are set up in the study for both manual and computer calculation of transport costs and methods of escalation. This section represents a very general summary of the information in the EPA study. Time and space do not permit a presentation of the total calculation procedure nor complete breakdown of cost estimates, so only total cost typical, current information is provided. A copy of the EPA study, Contract No. 68-03-2186, should be obtained if greater detail is needed.

The total costs for sludge transport consist of:

1. Point to point transport costs including capital and O & M.

2. Facilities capital and O & M costs. (In case of truck, barge, and railroad. Facilities include:

	Transport Mode		
Liquid	Truck	Railroad	Barge
Loading Storage	No(2)	Yes	Yes
Loading Equipment	Yes	Yes	Yes
Dispatch Office	Yes	Yes	Yes
Dock and Control Bldg.	N/A	N/A	Yes
Railroad Siding(s)	N/A	Yes	N/A
Unloading Equipment	Yes	Yes	Yes
Unloading Storage (1)	No	No	No

Dewatered	Truck	Railroad	Barge
Loading Storage	Yes(3)	Yes	N/A
Loading Equipment	Yes	Yes	N/A
Dispatch Office	Yes	Yes	N/A
Dock and Control Bldg.	N/A	N/A	N/A
Railroad Siding(s)	N/A	Yes	N/A
Unloading Equipment	Yes	Yes	N/A
Unloading Storage (1)	No	No	N/A

(1) Storage assumed to be a part of another unit process.

(2) Storage required for one or two truckloads is small compared with normal plant sludge storage.

(3) Elevated storage for ease of gravity transfer to trucks.

Pipeline facilities consist of pipeline and pumping stations.

The forms of sludge studied and the transport modes are:

	Form of Sludge	
Transport Mode	Liquid	Dewatered
Truck	X	X
Barge	X	
Railroad	X	X
Pipeline	X	

The most common liquid sludge concentration is 1 to 4 percent solids although liquid sludge up to 10 percent solids can be handled with relative ease. Dewatered sludges are normally 15 to 20 percent solids and can be moved with belt conveyors or similar handling systems.

TRUCK TRANSPORT

Truck is widely used for transport of both liquid and dewatered sludges. This mode offers flexibility because the terminal points and route of haul can be changed readily and at low cost. Investment in terminal facilities can be minimal. Many truck configurations are available ranging from standard tank and dump bodies to very specialized equipment for hauling and spreading sludges. Trucks can be purchased or leased or the hauling contracted to a private operator. The generalized cost curves presented are based on the following criteria and assumptions:

1. Most economical type truck from selection of standard frame or semi-trailer mounted bodies; tanks for liquid and dump or ram type for dewatered.

2. Eight hours of trucking operation per day.

3. Fuel cost at $0.60 per gallon.

4. Amortization of truck capital cost over 6 years at 7 percent.

5. Truck O & M cost, excluding fuel and operator, $0.20 to 0.30 per mile depending on type of truck.

6. Truck loading time 30 minutes and unloading time 15 minutes.

7. Truck average speed 25 mph for first 20 miles one way and 35 mph for rest.

8. General and administrative costs 25 percent of total O & M cost.

9. Sludge densities: Liquid - 62.4 lbs/cf; Dewatered - 55 lbs/cf; Ash - 50 lbs/cf.

In general, the total cost of truck transport will be decreased (per unit of material hauled) if the daily period of truck operation is increased. Restrictions may be placed on any significant truck operations such as specific routes or daylight hours for operations. The larger trucks are the most economical except for one way haul distances less than ten miles and annual sludge volumes less than 3,000 cubic yards for dewatered sludge and for less than one million gallons per year for liquid sludge. Generally, diesel engines are used in the larger trucks and are the economical choice for small trucks when operated at high annual mileage. Table 20 summarizes truck transport costs for a variety of sludge types and haul distances.

BARGE TRANSPORT

Barge transport has been used in the past for ocean disposal of sludges, but barge can be used for transport of sludges between land points that are connected by navigable waterways. The use of barges is limited to those locations in reasonable proximity to suitable waterways.

Barges have been used in the past for transport of liquid sludges and no applications for dewatered sludges are known. Barges can be leased or purchased or the barging can be performed by an outside private operator. In most cases, the towing is subcontracted to a tug operator. Self propelled barges have been used in New York City for many years but, except for special cases, separate tugs and barges offer more flexibility.

In general, the large barges are much more cost effective than smaller barges. Larger barges have deeper drafts and, therefore, may not be practical for many inland waterways. The major factor in barging is the cost of tug (towing) services and the larger barges minimize this cost.

TABLE 20

TRUCK TRANSPORT COSTS

10 Tons Dry Solids Per Day

SLUDGE TYPE	% SOLIDS	COST, $/TON (DRY SOLIDS) ONE WAY HAUL, MILES 5	10	20	40	80
	4	$35.60	$46.60	$74.00	$120.50	$200.00
LIQUID	7	21.90	30.10	46.60	71.20	123.30
	11	17.50	21.40	35.60	49.30	79.50
DEWATERED	20	15.90	19.70	24.10	35.60	49.30
	40	11.50	13.40	15.90	19.20	26.30
DRIED	95	9.00	10.40	11.20	12.90	15.90
ASH	100	7.10	8.00	9.00	10.10	11.80

25 Tons Dry Solids Per Day

SLUDGE TYPE	% SOLIDS	COST, $/TON (DRY SOLIDS) ONE WAY HAUL, MILES 5	10	20	40	80
	4	$29.60	$41.60	$68.00	$116.50	$198.20
LIQUID	7	18.60	24.10	41.60	68.00	120.60
	11	14.30	18.60	28.50	47.10	77.80
DEWATERED	20	10.10	14.30	19.70	28.50	48.20
	40	6.90	8.80	11.00	17.50	25.20
DRIED	95	4.70	5.60	6.50	8.10	10.70
ASH	100	4.05	4.40	4.90	5.70	7.20

TABLE 20 (Cont'd)

50 Tons Dry Solids Per Day

SLUDGE TYPE	% SOLIDS	COST, $/TON (DRY SOLIDS) ONE WAY HAUL, MILES 5	10	20	40	80
LIQUID	4	$26.90	$39.50	$65.80	$109.60	$191.80
	7	16.40	23.00	38.40	76.70	109.60
	11	11.50	15.30	26.30	44.90	76.70
DEWATERED	20	8.80	10.40	15.90	26.90	47.10
	40	4.90	7.10	9.30	14.30	23.60
DRIED	95	3.20	4.00	4.90	7.10	10.40
ASH	100	2.40	2.70	3.20	4.10	5.50

100 Tons Dry Solids Per Day

SLUDGE TYPE	% SOLIDS	COST, $/TON (DRY SOLIDS) ONE WAY HAUL, MILES 5	10	20	40	80
LIQUID	4	$27.40	$33.80	$54.80	$104.10	$191.80
	7	15.40	23.00	35.60	65.80	106.90
	11	10.40	15.10	24.40	46.60	74.00
DEWATERED	20	6.30	8.50	14.30	26.30	46.60
	40	4.40	5.20	8.00	13.40	23.60
DRIED	95	2.30	3.30	4.40	6.00	10.10
ASH	100	1.60	2.00	2.50	3.60	5.20

The information in this section is based on barges up to 850,000 gallon capacity, but barges are available in sizes to two million gallons and greater. These larger sizes will substantially reduce the cost of transport for medium to large installations, but the larger barges may be too large for some inland waterways. As an example, for an annual sludge volume of 150 million gallons and a one way haul distance of 150 miles, the total annual cost using two million gallon capacity barges would be half of the total annual cost using 850,000 gallon barges.

The generalized cost curves were based on the following criteria and assumptions:

1. Most economical barge size up to 850,000 gallons.

2. Single barge per tow.

3. Towing services contracted to outside tug operator.

4. Amortization of barge cost over twenty years at 7 percent.

5. Barge loading and unloading time five hours each.

6. Barge average towing speed 4 mph.

7. Barges not manned during tow.

8. General and administrative costs 25% of total O & M cost.

Barge transit times will be variable depending on traffic, draw bridges, locks, tides, currents, and other factors. The 4 mph speed is an average and speeds in open water may exceed 7 mph. Barges are normally unmanned during transit.

Loading can be accomplished by either a gravity pipeline or pump(s) and pipeline from a storage tank. A barge is normally filled in 2-5 hrs.

Unloading requires a pump(s) for transfer of sludge to a storage system. The pump can be barge or dock mounted and can be diesel or electric.

The use of barge was limited to liquid sludge because of the difficulty of unloading dewatered sludge from a barge and because of lack of full scale experience.

Table 21 summarizes barge transport costs.

RAILROAD TRANSPORT

It is hard to obtain information on railroad transport for generalized cases. Most rail companies prefer to deal in specific cases. There are very few actual cases of rail transport of sludges at present, so there is little experience from which to draw information.

TABLE 21

BARGE TRANSPORT COSTS

SLUDGE % SOLIDS	COST, $/TON (DRY SOLIDS) ONE-WAY HAUL, MILES 20	40	80	160	320
10 TONS DRY SOLIDS PER DAY					
4	$82.20	$93.20	$117.80	$161.60	$268.50
7	68.50	82.20	98.60	123.30	189.00
11	63.00	74.00	87.70	106.90	139.70
25 TONS DRY SOLIDS PER DAY					
4	$48.20	$60.30	$ 87.70	$142.50	$230.00
7	38.40	43.80	57.00	85.50	153.40
11	32.90	37.30	48.20	64.70	93.20
50 TONS DRY SOLIDS PER DAY					
4	$34.00	$49.30	$ 76.70	$120.50	$219.20
7	25.80	31.80	46.60	71.20	142.50
11	21.36	25.80	35.10	50.40	93.20
100 TONS DRY SOLIDS PER DAY					
4	$27.40	$46.60	$ 71.20	$115.10	$216.40
7	18.90	27.40	43.80	68.50	137.00
11	14.50	19.50	30.10	46.60	90.40

Rail cars can be leased from manufacturers on a full maintenance basis. This would be the best method to assure a continuous supply of cars in good running condition. Rail companies provide a rebate of approximately $0.06 to $0.20 per loaded mile (depending on condition of the car) to compensate the shipper for providing his own cars. The number of cars required is related to the round trip transit time. Transit times have a significant effect on the number of rail cars needed and, hence, on capital or lease costs. Even with careful planning it would be difficult to reduce rail transit time, even between close points, to less than three days round trip because of train make-up, switching, and weighing. Round trip transit time typically will be four to eight days for one way haul distances of 20 to 320 miles.

Rail rates vary widely, but in general rates in various parts of the country vary according to the following table:

Area	Approximate Railroad Rate Variation
North Central and Central -	Average
Northeast	25% Higher than Average
Southeast	25% Lower than Average
Southwest	10% Lower than Average
West Coast	10% Higher than Average

The following rates were used in preparing costs:

One Way Distance, Miles	Rate, $/Net Ton
20	2.10
40	3.00
80	4.10
160	6.50
320	12.20

Table 22 presents typical costs.

PIPELINE TRANSPORT

There are many choices to be made in the design of a sludge pipeline system. The following assumptions were made for purposes of this paper and are representative of design criteria used in actual designs. The liquid sludge was assumed to be reasonably free of grit and grease, similar to anaerobically digested material. Raw sludge can also be transported by pipeline, but the grease may require additional maintenance procedures. The solids content does not affect the calculations within the range of 0-4 percent solids. The minimum pipeline size is 4 inch. The literature describes installations with smaller pipelines, but these small pipelines represent special design cases.

Sludge pumps are of the dry pit, horizontal or vertical, non-clog, centrifugal type which are widely used for sludge pumping applications. Because of the high friction loss in 4 and 6 inch pipelines, pumping stations for these lines contain more than one pump in series in order to develop higher pumping heads and minimize the number of stations. Two pumps are operated in parallel for the 16, 18, and 20 inch pipelines because of the high flows. Each pumping station contains facilities for pipeline cleaning using plastic pigs and macerators.

TABLE 22

RAILROAD TRANSPORT COSTS

10 Tons Dry Solids Per Day

SLUDGE TYPE	% SOLIDS	COST, $/TON (DRY SOLIDS) ONE WAY HAUL, MILES 5	10	20	40	80
LIQUID	4	$87.70	$104.10	$134.30	$205.50	$356.20
	7	54.80	65.80	82.20	197.30	350.70
	11	43.80	52.10	65.80	85.00	137.00
DEWATERED	20	25.20	35.60	41.10	49.30	82.20
	40	17.30	19.70	22.50	27.10	46.60
DRIED	95	-	-	-	-	-
ASH	100	-	-	-	-	-

25 Tons Dry Solids Per Day

SLUDGE TYPE	% SOLIDS	COST, $/TON (DRY SOLIDS) ONE WAY HAUL, MILES 5	10	20	40	80
LIQUID	4	$84.40	$101.90	$131.50	$197.30	$350.90
	7	49.30	59.20	74.50	120.60	208.20
	11	34.00	40.60	52.60	81.10	131.50
DEWATERED	20	18.60	21.90	28.50	39.50	68.00
	40	12.10	15.30	18.60	21.90	38.40
DRIED	95	6.80	8.00	9.20	10.90	18.60
ASH	100	-	-	-	-	-

TABLE 22 (Cont'd)

50 Tons Dry Solids Per Day

SLUDGE TYPE	% SOLIDS	COST, $/TON (DRY SOLIDS) — ONE WAY HAUL, MILES: 5	10	20	40	80
LIQUID	4	$82.20	$98.60	$126.00	$191.80	$339.70
	7	46.60	54.80	71.20	115.10	202.70
	11	31.20	38.40	48.20	76.70	128.80
DEWATERED	20	13.20	19.20	24.10	35.60	65.80
	40	8.80	11.00	14.30	19.70	34.00
DRIED	95	5.10	7.10	8.20	9.90	15.90
ASH	100	3.50	4.10	4.60	6.00	9.30

100 Tons Dry Solids Per Day

SLUDGE TYPE	% SOLIDS	COST, $/TON (DRY SOLIDS) — ONE WAY HAUL, MILES: 5	10	20	40	80
LIQUID	4	$79.50	$98.63	$123.30	$189.00	$328.80
	7	43.80	49.30	65.80	101.40	186.30
	11	30.10	37.00	46.60	74.00	126.00
DEWATERED	20	12.90	18.40	23.80	34.30	63.00
	40	7.40	9.90	12.30	18.60	32.90
DRIED	95	4.10	4.90	6.30	8.20	14.50
ASH	100	2.70	3.60	4.40	4.90	8.80

The pipeline is cement lined cast iron or ductile iron pipe which is typical for sludge pipelines. The cement lining provides long life and a smooth interior surface. Installation is assumed to be in normal soil conditions with average shoring and water problems typical to shallow force main installations. Installation is assumed to be above hard rock. The pipeline cost included one major highway crossing per mile and one single track railroad crossing per five miles plus a number of driveway and several minor road crossings per mile. These costs should be typical for average installations to be expected for sludge pipelines.

The pipelines in this study were designed based on an operating velocity of 3 fps. The depth of the pipeline will not affect the capital cost within the range of 3 to 6 feet of burial in normal soil. Facilities at the discharge end of the pipeline such as lagoons, dewatering equipment, or spreading equipment are assumed to be a part of other unit processes. Table 23 presents typical costs.

The following general conclusions on sludge transport costs may be reached:

Liquid Sludges of 4% Solids

- At 10 Tpd (dry solids) capacity, pipeline is the cheapest method for distances up to 30 miles, and barge is the cheapest for greater distances.

- For 4 percent solids at a 25 Tpd (dry solids) capacity, pipeline is the choice for distances up to 55 miles, and barging at greater distances.

- For plant capacities of 50 Tpd (dry solids) or more, pipeline transport is the most economical method for all transport distances.

Liquid Sludges of 7 and 11 Percent Solids

- Truck hauling is typically lowest in cost for distances up to 20 to 30 miles.

- For distances greater than 20 miles and for plant capacities exceeding 10 Tpd (dry solids), barge or rail transport is less expensive than trucking.

Sludge Cake and Ash

- At sludge solids concentrations greater than 20 percent, usually the only alternates considered are truck and rail transport.

- For plant capacities of 10 Tpd (dry solids) or less, truck transit is cheaper.

- For plant capacities greater than 10 Tpd (dry solids), truck and rail transport are competitive for hauls between 20 and 80 miles; below 20 miles, trucking is cheaper; and over 80 miles, rail transit is cheaper.

TABLE 23

PIPELINE TRANSPORT COSTS

10 TONS DRY SOLIDS PER DAY

SLUDGE % SOLIDS	COST, $/TON (DRY SOLIDS) DISTANCE, MILES 5	10	20	40	80	160	320
0 TO 4	$14.10	$28.20	$56.40	$112.80	$225.60	$451.20	$902.40
25 TONS DRY SOLIDS PER DAY							
0 TO 4	$ 6.30	$12.60	$25.10	$ 50.20	$100.50	$200.90	$401.90
50 TONS DRY SOLIDS PER DAY							
0 TO 4	$ 3.30	$ 6.60	$13.10	$ 26.30	$ 52.50	$105.00	$210.10
100 TONS DRY SOLIDS PER DAY							
0 TO 4	$ 1.70	$ 3.50	$ 7.00	$ 13.90	$ 27.80	$ 55.60	$110.20

SECTION VII

ALTERNATIVE SYSTEMS

There are many combinations (some of which are summarized by Figure 1) of the unit processes for sludge handling that may be worthy of consideration in a specific region. Among the factors which must be considered for each alternative system are:

- Costs
- Energy Requirements
- Environmental Impacts
- Availability (current and future) of consumables required (chemicals, fuel, electricity).
- Land Requirements
- Operation Skills Required
- Potential for resource recovery and resulting economic benefits from the sludge or from sludge processing by products (i.e., digester gas, waste heat from incinerator).
- Potentials for implementation delays (acquisition of land, rights-of-ways for pipelines, sensitive environmental issues involved).
- Status of Technology Involved (demonstrated at plant scale, pilot scale, etc.)
- Experience with process(es) at other locales.
- Compatibility with existing local, state, and federal guidelines and regulations.

Energy implications may be particularly significant in the future. One recent study[83] concluded that relatively high energy requirements for aerobic digestion, sludge (heat) drying, and incineration of sludges with low solids content ($\leq$ 20-25 percent solids), will make these options economically less competitive (but not necessarily non-competitive) in the future.

The preceding sections represent a brief summary of the major considerations associated with many unit processes that may be combined into a sludge handling system. Although there are several factors to be considered, costs must be a major consideration. Table 24 presents a summary of factors for major unit process alternatives. Ten and 100 ton/day systems are tabulated to illustrate typical costs and the effects of scale on the various processes. As noted earlier, costs must be carefully evaluated for local conditions and these illustrative costs are offered to merely provide an overall perspective of relative costs. The reader should refer to the earlier sections of this paper and associated references for discussion of the factors that may effect costs.

Individual unit process costs in themselves do not reflect the overall economic competitiveness of a unit process. For example, filter press costs are typically higher than vacuum filtration or centrifugation costs; however, the higher degree of dewatering achieved by the filter press may result in significant economies in the downstream disposal process whether it be incineration or landfill. Typical system costs are presented in Figure 23 to provide still another perspective on costs. There are many other possible combinations but these illustrate some of the most often considered alternatives.

TABLE 24. COMPARISON OF PROCESSES FOR PRIMARY PLUS WAS SLUDGES

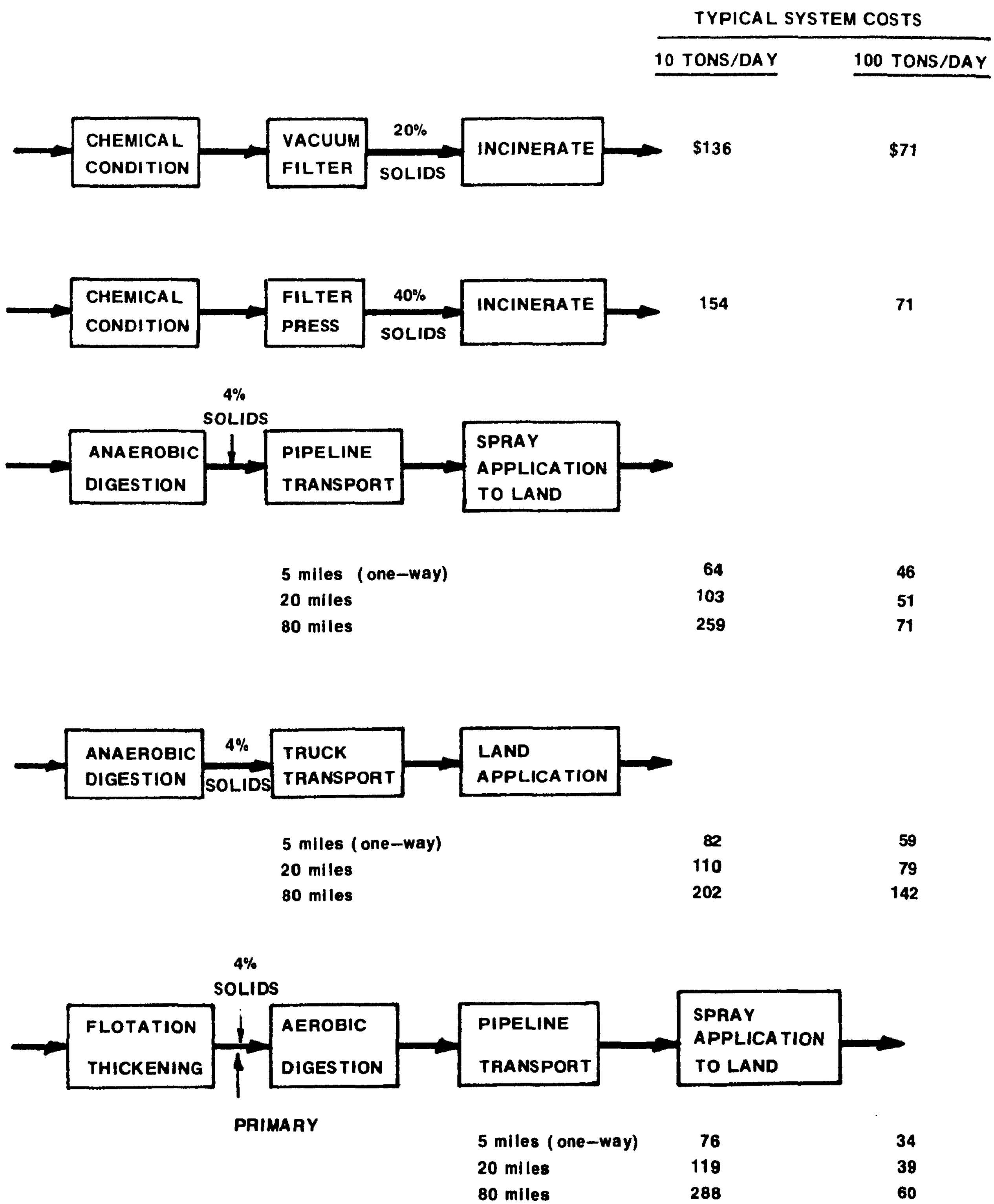
	CONDITIONING		THICKENING		DEWATERING					INCINERATION		DIGESTION		HEAT DRYING (4)	DRYING BY SOLVENT EXTRACTION	COMPOSTING (4)	TRANSPORT
	HEAT TREATMENT	CHEMICAL	GRAVITY	FLOTATION	DRYING BEDS	VF (3)	CENTRIFUGE (3)	FILTER PRESS (3)	LAGOONS	SOLIDS % 20	40	AEROBIC	ANAEROBIC				
Typical Costs ($/Ton) 10 T/Day 100 T/Day	75 42	10–25 10–25	5 2	11.60 6	70–90 N/A	43 25	37 22	76 40	10–20 10–20	95 45	54 31	46 22	47 41	100 63	95 62	40 30	10–300 per ton
Typical Energy Requirements kwh/Ton Btu/Ton	100–150 3x10^6	Minimal –	1–1.5 –	100 –	– –	40–60 –	200–400 –	50–200 –	– –	50–90 8–10x10^6		1200–1500 –	150–200 –	200–300 8–16x10^6	500–700 6–7x10^6	Dependent on Compost Method	Can be sig.– see Transport Section
Land Requirements	Minimal	Minimal	Minimal	Minimal	Approx. 1 acre/ton/day	Minimal	Minimal	Minimal	Approx. 15 acres/ton / day	Minimal		Minimal	Minimal	Minimal	Minimal	0.2–1 acre/ton	–
Operator Skills Required (2)	10	2	2	4	1	4	7	4	1	8		4	8	10	8	4	–
Resource Recovery Potential	Heat Recovery	None	None	None	Dewatered Sludge to Land					Heat Recovery		None	Energy From Gas (1)	Dried Fertilizer		Soil Conditioner	–
Potential For Delays	–	–	–	–	Land	–	–	–	Land	–		–	–	–	Agency Approval	Compost Site	Rights of way
Status of Technology	Wide Use but Problems Common	Wide Use	Wide Use	Wide Use	Wide Use	Wide Use	Wide Use	Wide Use	Wide Use	Wide Use		Wide Use	Wide Use	Very limited Use	In Development Stage	Limited use to Date	–
Compatibility With Regulations	Impact on Effluent Quality Odors									Must include Provisions for Air Poll. Control				Air Pollution Standards may not be met		Some Agencies Do Not Yet have Regulations Developed	

(1) Can produce about $6x10^6$ Btu/Ton.
(2) 10 = very highly skilled; 1 = minimal skills – includes maintenance and operation considerations.
(3) Costs include chemical conditioning.
(4) Costs do not include credit for potential sale of resulting product.

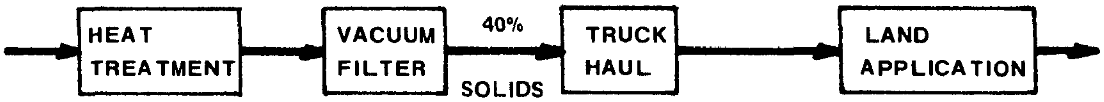
Figure 23

TYPICAL SLUDGE HANDLING (PRIMARY+ WAS)

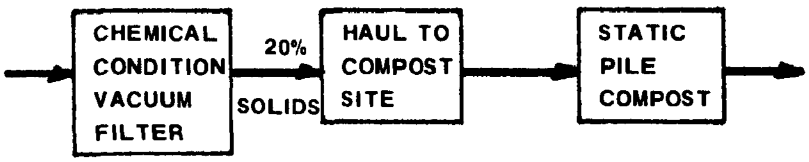
SYSTEM COSTS PER TON OF DRY SOLIDS



	TYPICAL SYSTEM COSTS	
	10 TONS/DAY	100 TONS/DAY



	10 TONS/DAY	100 TONS/DAY
5 miles (one–way)	$ 135	74
20 miles	140	77
80 miles	150	93



	10 TONS/DAY	100 TONS/DAY
0 miles	80	56
5 miles (one–way)	96	62
10 miles	100	65

(Does not include potential income from sale of compost)

	10 TONS/DAY	100 TONS/DAY
	180	104

(Does not include potential income of $30/ton from sale of dried product)

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