COST AND ENERGY REQUIREMENTS OF SLUDGE HANDLING AND ULTIMATE LAND DISPOSAL METHODS

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ABSTRACT

COST AND ENERGY REQUIREMENTS OF
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A sequential decision model known as dynamic programming was used to analyze cost and energy consumption for 15 processes involved in sewage sludge treatment. Three conditions were considered: (1) the economic optimum using capital costs, operating power, and labor; (2) the optimum for an energy poor future using capital costs and operating power and; (3) the energy optimum using capital and operating energy.

For the first case dissolved-air flotation, aerobic digestion and lagooning was found to be the best treatment scheme at a flow of 1 million gallons per day (MGD). For 10 MGD and 100 MGD the best treatment scheme was found to be gravity thickening, anaerobic digestion and lagooning. No change was found in these treatment schemes for case 2. For case 3, the best treatment scheme was found to be gravity thickening, anaerobic digestion and lagooning for all 3 design flows.

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INTRODUCTION

Most methods of municipal wastewater treatment have an end product of large quantities of sewage sludge. This amounts to some 4.2 million tons per year in the United States alone.[1] It comprises about 50% of the total treatment cost and 90% of the operators headaches. The characteristics of the sludge vary both with source (i.e.: industrial or municipal), and with the sewage treatment process employed (i.e.: physical, chemical, or biological). These variations dictate the choice of sludge treatment.[2]

The choice of sludge treatment must be made with regards to costs and energy requirements. The ultimate goal of any well managed community is to use the treatment scheme that will have the best cost-performance ratio and also the lowest energy consumption. Energy consumption not only includes the operating energy, but also the amount of energy needed for materials fabrication used in treatment facilities (herein termed "capital energy" because of the analogy to capital costs). Energy is considered separately in order to investigate design decisions that would be made if the price of energy increases dramatically to become the dominant cost.

It is the purpose of this paper to present a comparative cost analysis of specific processes involved in sewage sludge treatment, and also to present a comparative energy consumption analysis of these same processes. The analysis is done under three conditions which are (1) the economical optimum for now and in the future, (2) the optimum for an energy affluent present with an energy poor future and (3) the energy optimum for now and the future.

The processes considered in this research are gravity thickening and dissolved-air flotation in the thickening step of sludge handling; anaerobic digestion, aerobic digestion and sludge lagooning in the stabilization stage of treatment; chemical conditioning, heat treatment and freezing in the conditioning process; vacuum filtration, centrifugation, filter pressing and sand bed drying in the dewatering stage; incineration and wet-air oxidation in the reduction of sludges; and landfilling, land application for soil conditioning, and lagooning in the final disposal step.

The sludge used in the above processes is a mixture of primary sludge (settled sewage from the primary sedimentation tanks) and activated sludge (wasted, biologically active solids from the secondary settling tanks).

LITERATURE REVIEW

THICKENING

Thickening or concentration is defined as removing water from sludge after its initial separation from wastewater.[3] The objective is to reduce the volume of liquid sludge to be handled in subsequent processes. Common types of thickening are gravity thickening, dissolved-air flotation, and centrifugation. Centrifugation is covered later under dewatering.

Gravity thickeners use natural gravity and gentle raking mechanisms to settle the sludge to the bottom of the tanks and thicken it. Costs, power, and labor requirements depend on the size of the thickening tanks, which in turn are dependent on the flow into the plant. The cost of the installed thickener, which includes price of thickener, erection, site preparation, pumps, piping, steel, instrumentation, electrical, paint and indirect costs has been depicted as a function of tank diameter.[4] The cost of an installed thickener increases as the tank size increases as seen in Figure 1.

The operating and maintenance (O and M) costs decrease with the increase in dry solids or flow. Generally, O and M costs for gravity thickeners at large plants are about $2.00 per ton of dry solids.[3] The construction costs, however, increase as the dry solids increase as shown in Figure 2.[5]

The raking mechanisms are the only part of the thickener that requires power. Table 1 shows the electrical power requirements for a one million gallon per day (MGD), 10 MGD and 100 MGD plant thickening primary and activated sludge.[6]

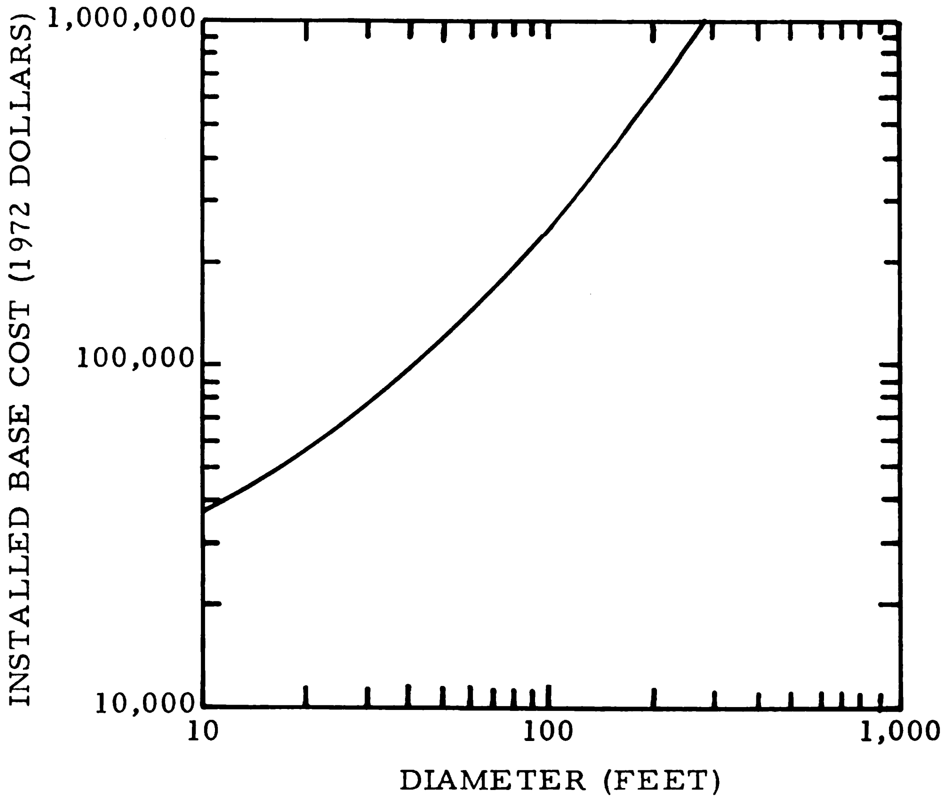
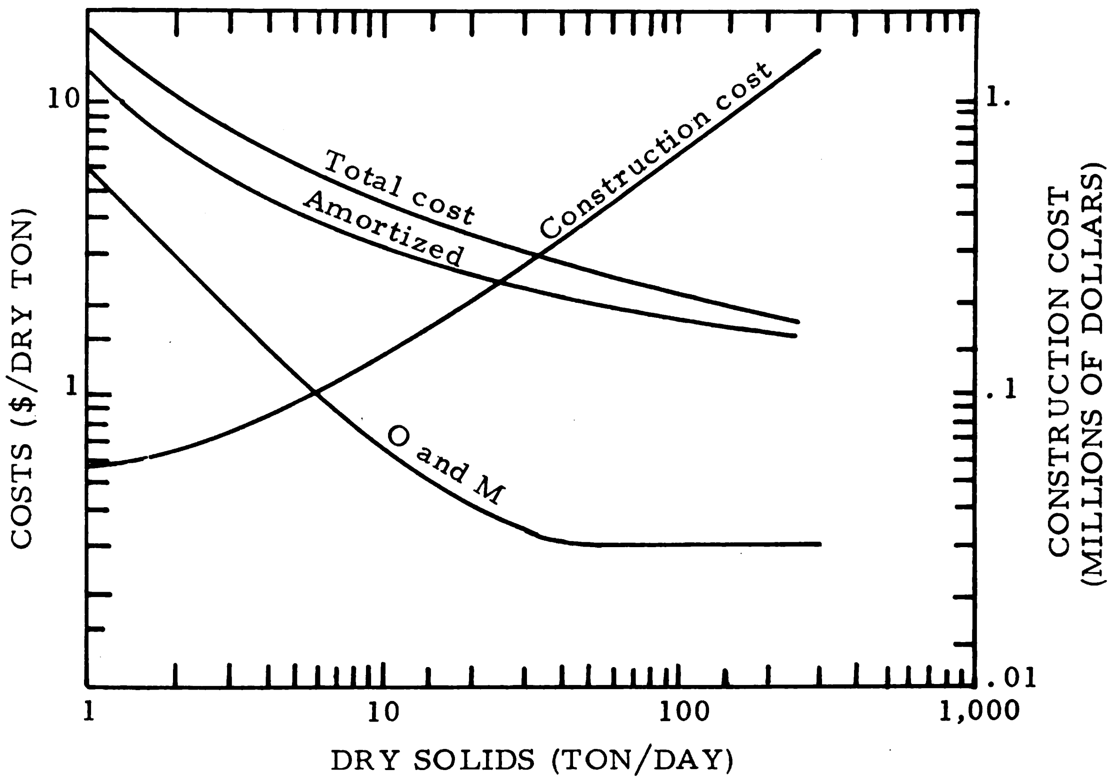


Figure 1. Gravity thickening capital cost [4]



Notes:

1. Minneapolis. Mar. 1972. ENR Construction Cost Index of 1827.
2. Amortization at 7% for 20 years.
3. Labor rate of $6.25 per hour.
4. No chemicals.
5. Influent sludge with a solids content of 0.5%.

Figure 2. Costs of gravity thickening [5]

TABLE 1

POWER CONSUMPTION

PLANT SIZE (MGD)	PRIMARY* (KWH/day)	ACTIVATED** (KWH/day)
1	10.2	10.2
10	20.4	20.4
100	30.6	40.8

*loading rate = 16 pounds/day/square foot ($lb/d/ft^2$)
**loading rate = 8 $lb/d/ft^2$

The labor requirement of a gravity thickener increases as the flow increases as shown in Figure 3.[7] Operational hours increase faster than the required maintenance hours.

In comparison to gravity thickeners, dissolved-air flotation (DAF) is cheaper initially but requires large amounts of power and chemicals. Dissolved-air flotation uses small air bubbles to raise all the sludge to the surface and collects it there and usually works best with waste activated sludge.[8]

The installed cost of a D.A.F. unit is based on the size of the pressure tank, which is dependent on the solids loading and sludge characteristics.[5] Figure 4 shows the comparison between the installed base cost and the tank capacity.[4] The machine has a lower capital cost than the gravity thickener but the expected lifetime is only half that of a gravity thickener.[4]

The process costs for the D.A.F. machine are given in Table 2 for various plant sizes.

TABLE 2

D.A.F. THICKENING COST

PLANT SIZE (MGD)	COST (DOLLARS/TON DRY SOLIDS)* O and M	AMORTIZATION	TOTAL
1	9.00	17.00	26.00
10	1.20	2.80	4.00
100	0.50	1.50	2.00

*Costs are based on: 1972 dollars, amortization at 7% for 20 years, labor rate of $6.25/hr, power cost of $0.01/KWH, no chemicals and a surface loading rate of 14.4 $lb/day/ft^2$.

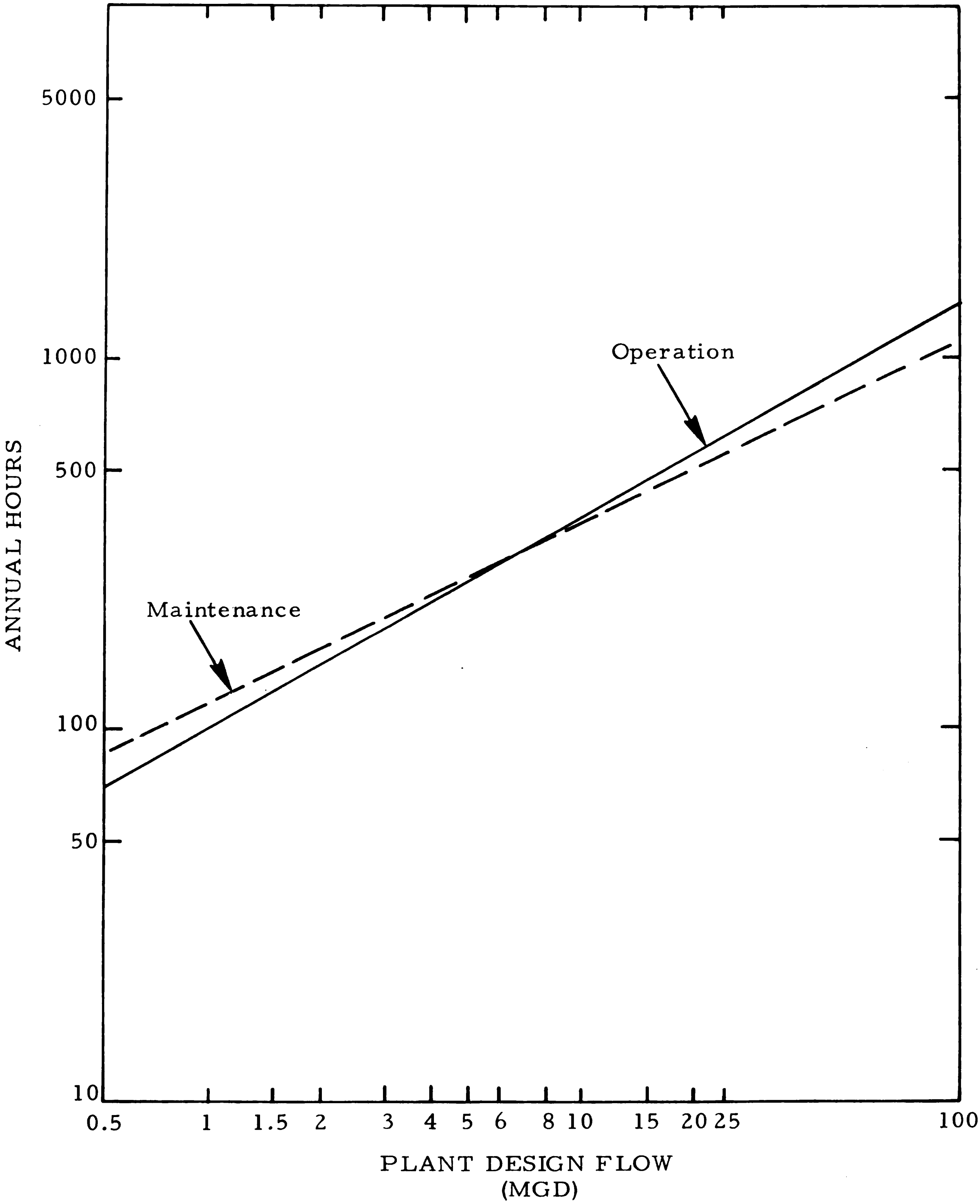


Figure 3. Gravity thickening labor requirements [7]

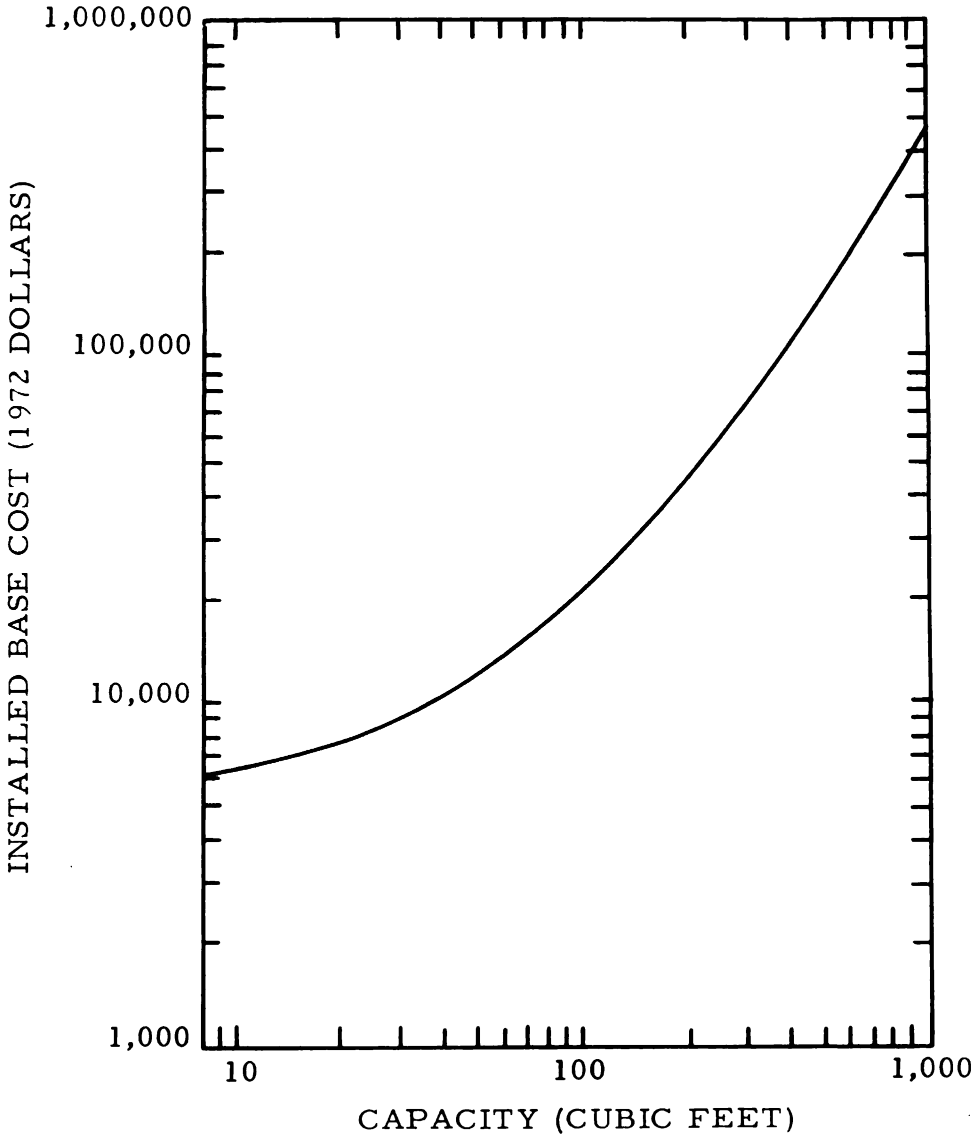


Figure 4. Dissolved-air flotation capital costs [4]

The O and M and total costs decrease rapidly as the plant size increases. Chemicals would add another $2.00 to $7.00 per ton to the total cost.[5] Even though the operating costs are high, the rate at which the sludge can be thickened is greater than the rate of a gravity thickener.[3]

The installed horsepower (Hp) of a D.A.F. unit is a function of thickener surface area. The electrical power consumption varies with the use of chemical thickening aids. Table 3 shows the electrical power used for various size plants with and without chemical aids.

TABLE 3

D.A.F. POWER CONSUMPTION

Plant Size (MGD)	Work Week	Required Hp	Power (KWH/day) W/Chemicals*	W/O Chemicals**
1	40	14.5	70	242
10	100	50.0	608	1800
100	168	230.0	4692	18800

*loading rate = 2 $lb/hr/ft^2$
**loading rate = 0.5 $lb/hr/ft^2$

The number of manhours required for using the D.A.F. is approximately twice that needed for the gravity thickener. Figure 5 shows that the operational hours increase faster than the maintenance hours as the design flow increases.[7]

STABILIZATION

The principle purposes of stabilization are to make the treated sludge less odorous and less putrescible, and to reduce the pathogenic organism population. The selection of a stabilization method depends primarily on the final disposal procedure planned for the sludge.

If the sludge is to be dewatered and incinerated, frequently no stabilization procedure is employed.[5] However, common types of stabilization used are aerobic digestion, anaerobic digestion, and lagooning. All three methods result in substantial decreases in the amount of suspended sludge solids in the system.

Aerobic digestion is the separate aeration of sludges. Cost depends primarily on the size of the tanks which is a function of waste

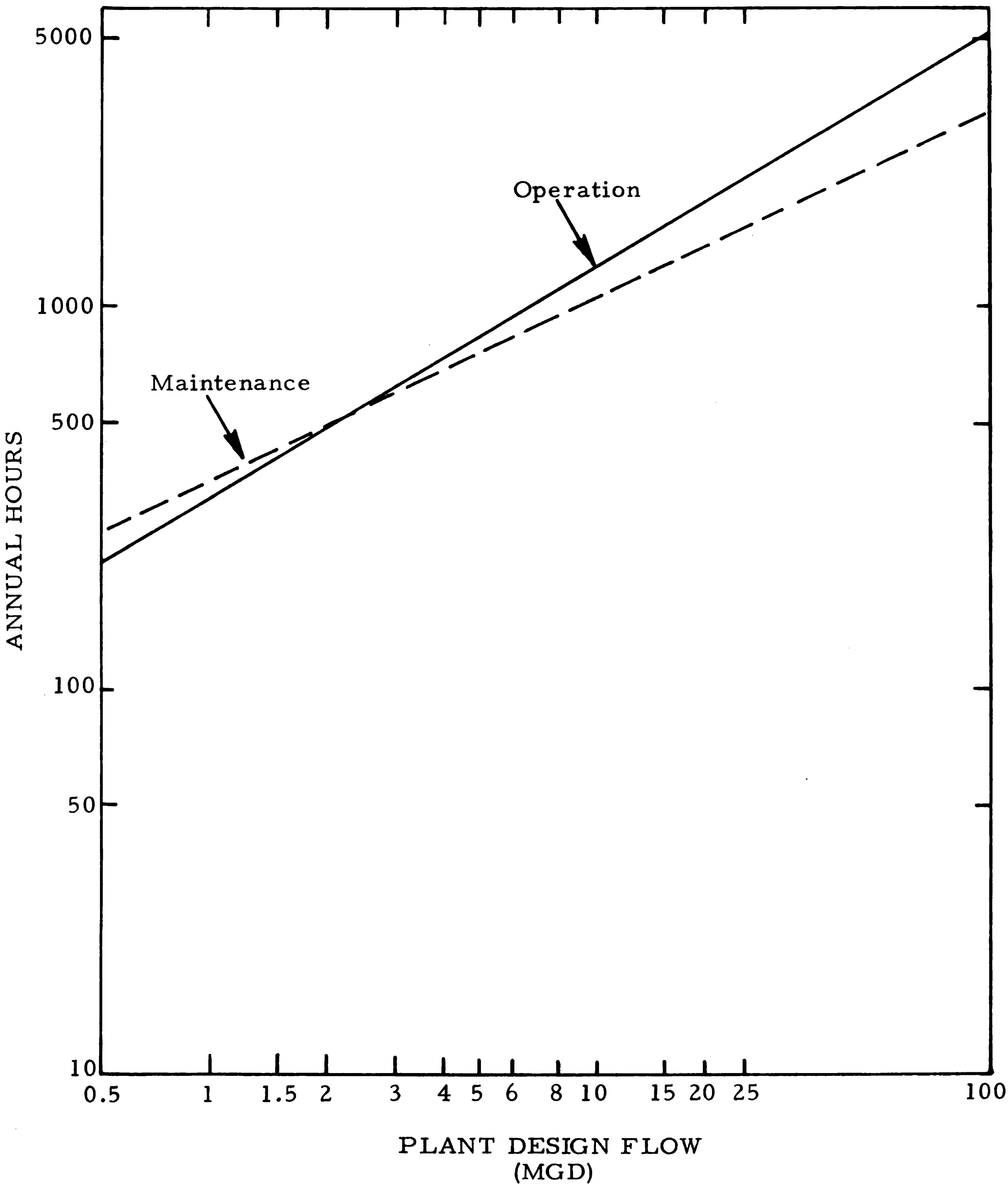


Figure 5. Dissolved-air flotation labor requirements [7]

sludge volume. Aerobic digestion tanks are normally uncovered and unheated, and are much cheaper to construct than covered, insulated, and heated anaerobic digestion tanks.[3]

Figure 6 shows the capital costs of aerobic digestion as a function of tons of dry solids per day.[5] In terms of liquid volume the construction costs of the basins for the digestion tanks are shown in Figure 7.[9] The construction cost of the basins increases at the same rate as the construction costs of the entire system as shown in Figure 6. The choice of aeration system, whether mechanical or diffused air, will change the amount of the initial cost.

Dorr-Oliver, in 1968, developed cost equations for the activated sludge process from available equipment information. These costs are similar to the capital cost of an aerobic digester with blowers. The equations are:[10]

Tank Capital Cost: $\text{LOG(COST)} = (0.806)\text{LOG}(V) + 0.306$

where COST = thousands of dollars and V = volume, 1000 ft^3.

Blower Capital Cost: $\text{COST} = 3.58(\text{CAP}) + 2.53$

where COST = thousands of dollars and CAP = capacity in 1000 standard cubic feet per minute (SCFM).

Blower Operating Cost: $\text{COST} = 0.68(\text{CAP}) + 0.14$

where COST = dollars per hour and CAP = capacity in 1000 SCFM.

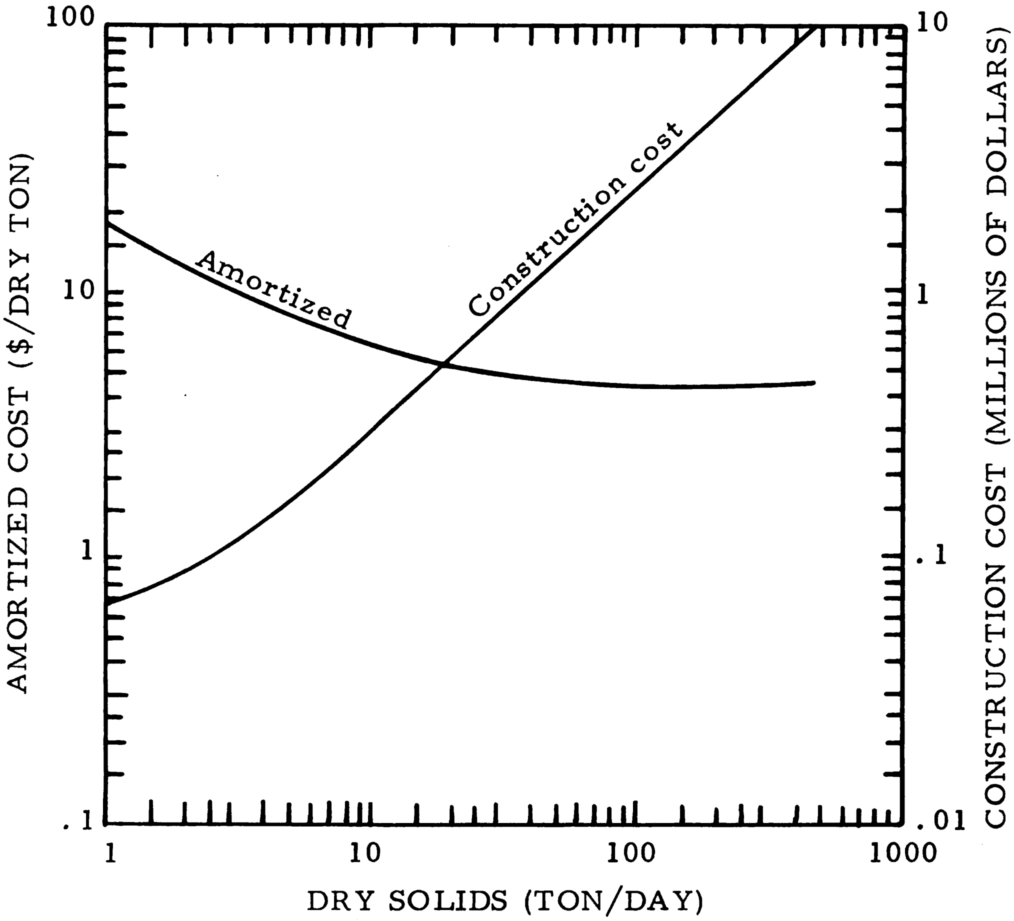
Mechanical Aerator Operating Cost: $\text{COST} = 1.42(V/100{,}000)$

where COST = dollars per hour and V = volume in ft^3.

The operating costs for the aerobic digesters are quite similar to the operating costs of the activated sludge tank. The major factor in the high operating costs of the aerobic digestion process is the power used in the blowers. About ten brake horsepower (BHp) per 10,000 population is required for aeration.[3]

The labor required for the operation and maintenance of aerobic digestion is shown in Figure 8. The operational hours are about five times the maintenance hours needed due to the air equipment.[7]

Anaerobic digestion has a higher capital cost than aerobic digestion due to the heaters required and tank coverings. Digestion tank volume requirements, to which construction costs are related, depend



Notes:

1. Minneapolis. Mar. 1972. ENR Construction Cost Index of 1827.
2. Amortization at 7% for 20 years.
3. Influent sludge of 38% primary and 62% waste activated sludge with a solids content of 3.5%.
4. 20 day volumetric displacement time.

Figure 6. Aerobic digestion capital cost [5]

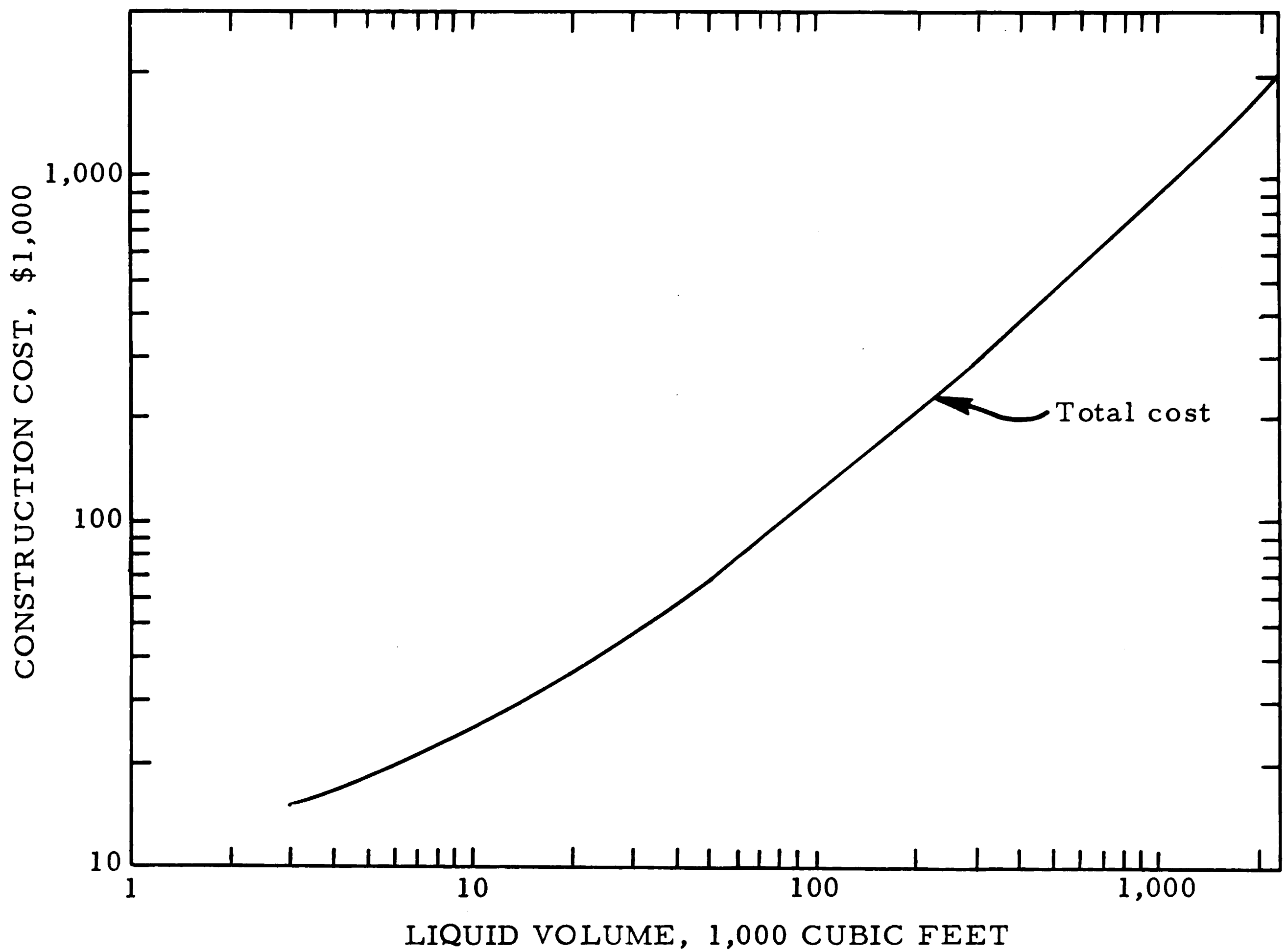


Figure 7. Aeration basin structure construction costs [11]

on temperature, sludge characteristics, storage requirements, quantity of sludge and the degree of digestion.[9]

Dorr-Oliver developed a capital cost equation for anaerobic digestion which includes all heating, mixing and gas requirements, sludge pumps, concrete tank requirements and a digester cover. The equation is:[10]

$$\mathrm{LOG(COST)} = 1/(0.31\ \mathrm{LOG}(V) + 0.37)$$

where COST = tenths of dollars per cubic foot and
V = volume in 1000 ft^3.

The volume of the tank depends on the type of sludge to be digested. Table 4 shows the comparison of tank volumes as a function of flow and sludge type.[6]

TABLE 4

DIGESTER TANK SIZES

PLANT SIZE (MGD)	VOLUME (FT^3) PRIMARY	ACTIVATED
1	8125	15,400
10	81,250	154,000
100	812,500	1,540,000

Activated sludge required about twice the tank volume of primary sludge.

Operating costs for anaerobic digestion vary between \$2.00 and \$4.00 per ton of sludge treated.[3] Figure 9 shows the O and M costs as they decrease when the digester volume increases, but over about 100,000 ft^3 the operating costs remain constant.[5]

Energy is consumed in anaerobic digestion by (1) heating the incoming sludge and holding the temperature at 95 degrees and (2) mixing the contents (gas recirculation). Table 5 shows the power needed for the sludge heating units in terms of plant size.[6]

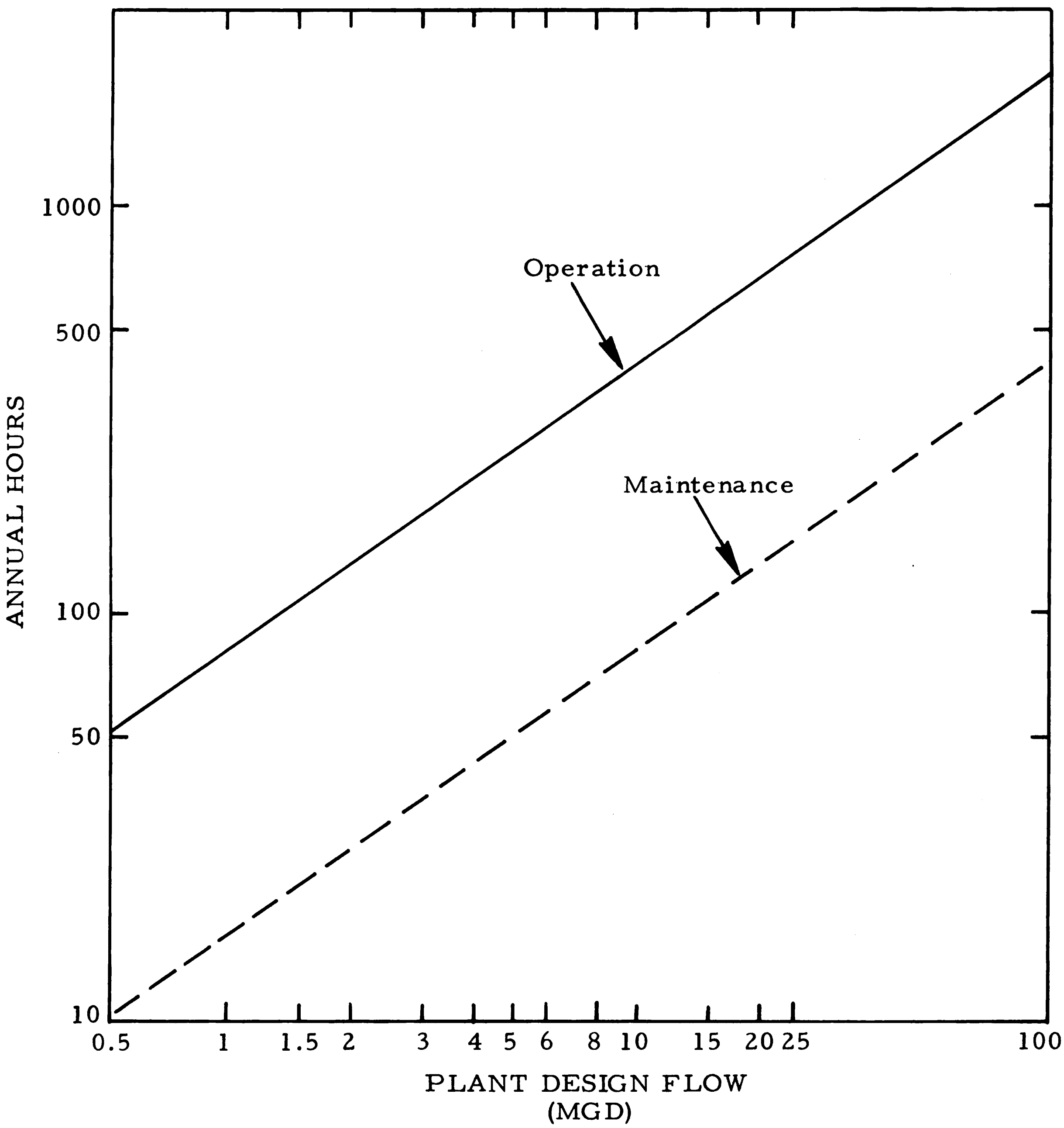
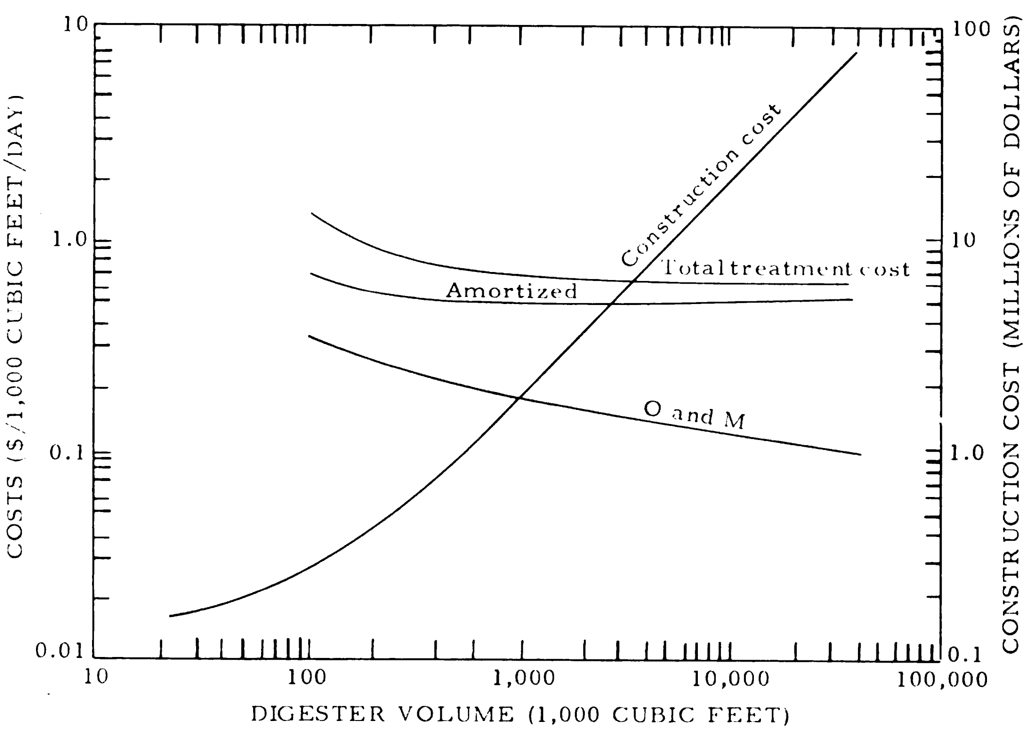


Figure 8. Aerobic digestion labor requirements [7]



Notes:

1. Minneapolis. Mar. 1972. ENR Construction Cost Index of 1827.
2. Amortization at 7% for 20 years.
3. Labor rate of $6.25 per hour.
4. Sludge heating, circulating and control equipment and control building included.

Figure 9. Unit anaerobic digestion costs [5]

TABLE 5

SLUDGE HEATING UNITS

PLANT SIZE (MGD)	POWER NEEDED(BTU/HR) PRIMARY	ACTIVATED
1	1 unit at 129,000	1 unit at 223,920
10	2 " 645,000	2 " 1,119,600
100	3 " 4,300,000	3 " 4,478,400

Table 6 shows the installed horsepower required and the electrical power consumption for the anaerobic digesters operating 75% of the time.[6]

TABLE 6

INSTALLED Hp AND ELECTRICAL POWER

PLANT SIZE (MGD)	No. of UNITS AND POWER (KWH/day) PRIMARY	ACTIVATED
1	1 unit at 6.0 Hp-100.8	1 unit at 6.4 Hp- 123.6
10	2 " 8.3 " 307.0	2 " 12.2 " 456.4
100	3 " 21.3 " 1146	5 " 21.3 " 1910

Tables 5 and 6 shows that activated sludge requires more energy than primary sludge, but the detention time or time required for digestion of the activated sludge is less than that of the primary sludge. This means the activated sludge can be processed faster than primary sludge.

The manpower required to operate and maintain the equipment involved in anaerobic digestion is approximately double that needed for aerobic digestion. Figure 10 shows higher operational hours than maintenance hours in relation to plant flow.[7]

Sludge lagoons can be used for either digestion, drying or both processes consequently. Construction costs of sludge lagoons are directly related to volume and the initial capital cost is dependent on local land rates. Figure 11 shows these construction costs and how they increase as the volume increases with no apparent economy of scale.[11]

The principle factor affecting the O and M costs of the lagoons is the quantity of material handled each year. Figures 12 and 13

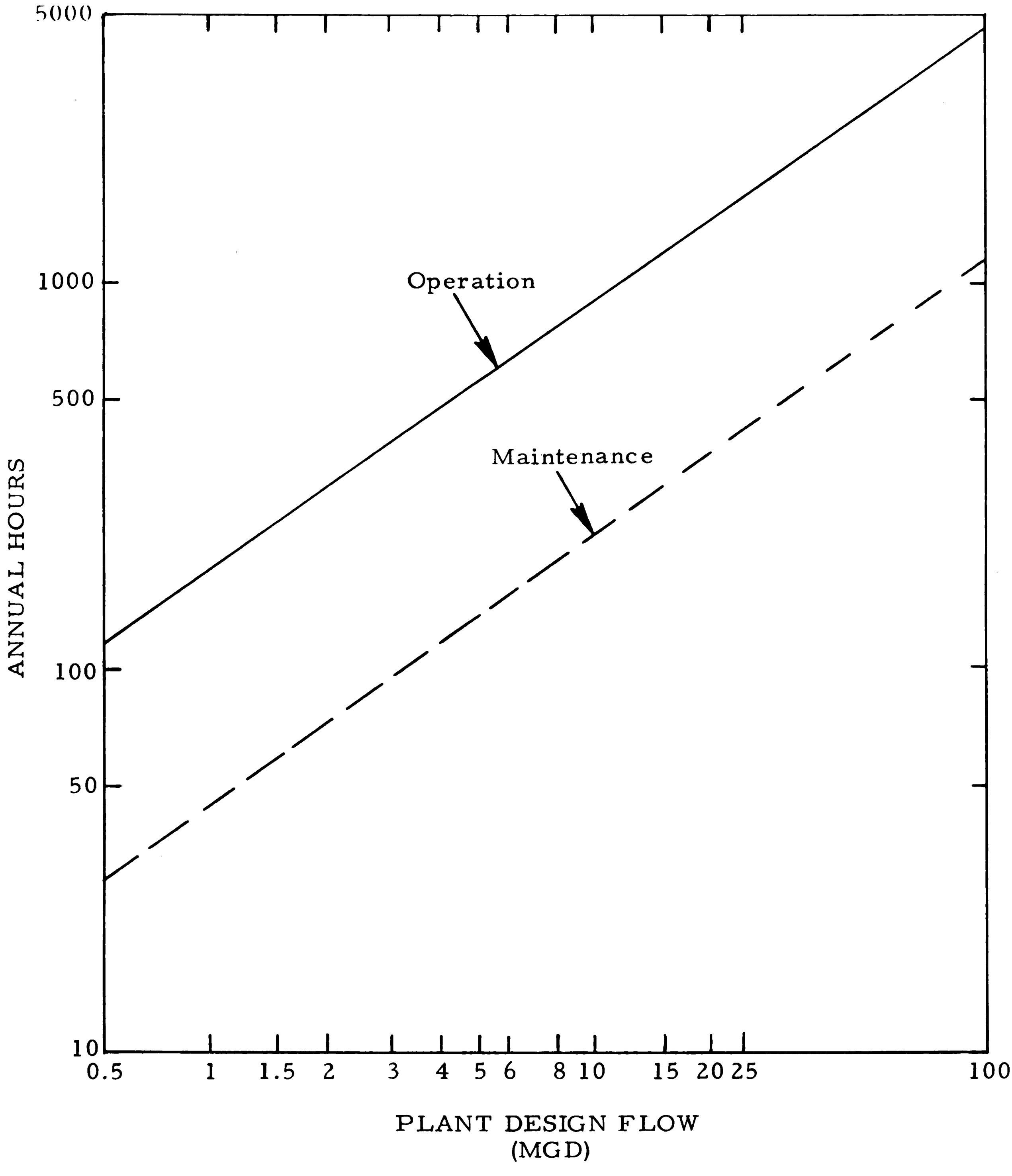


Figure 10. Anaerobic digestion labor requirements [7]

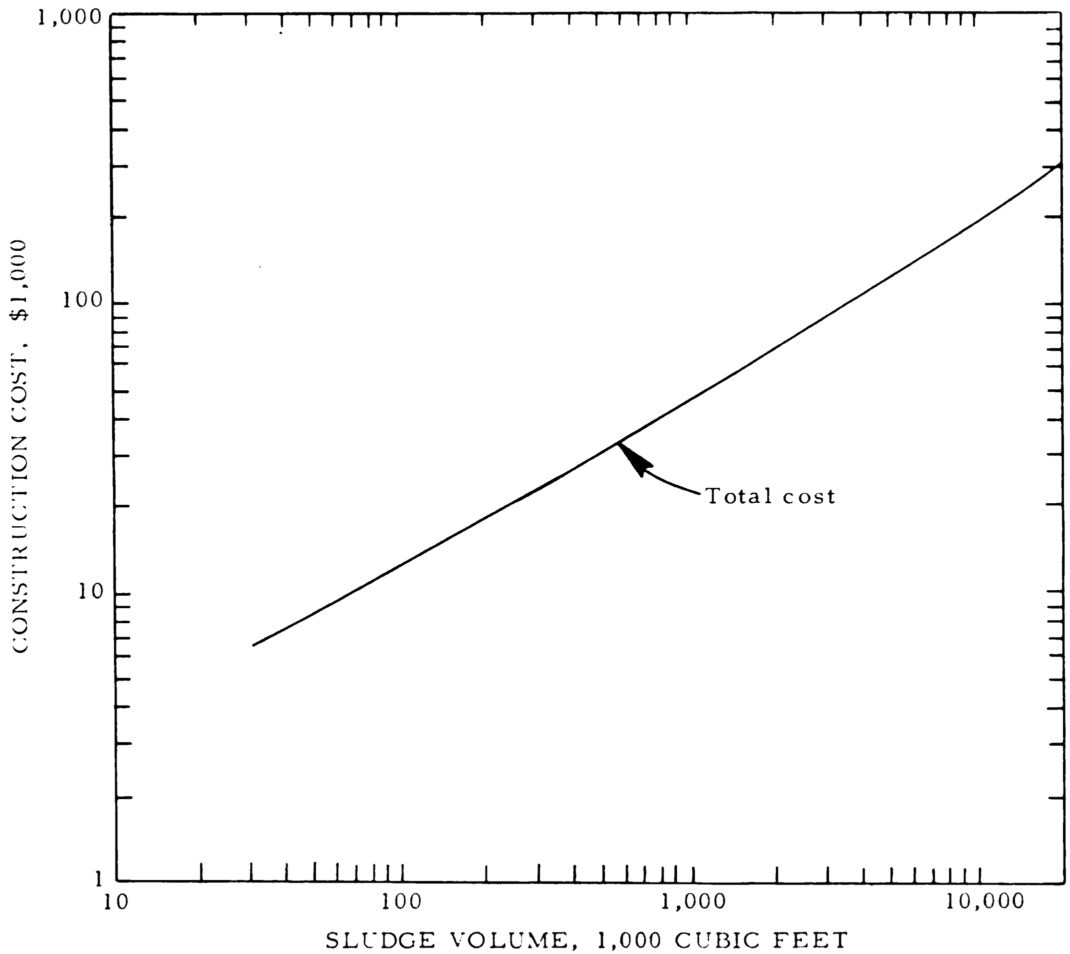


Figure 11. Sludge lagoon construction costs [11]

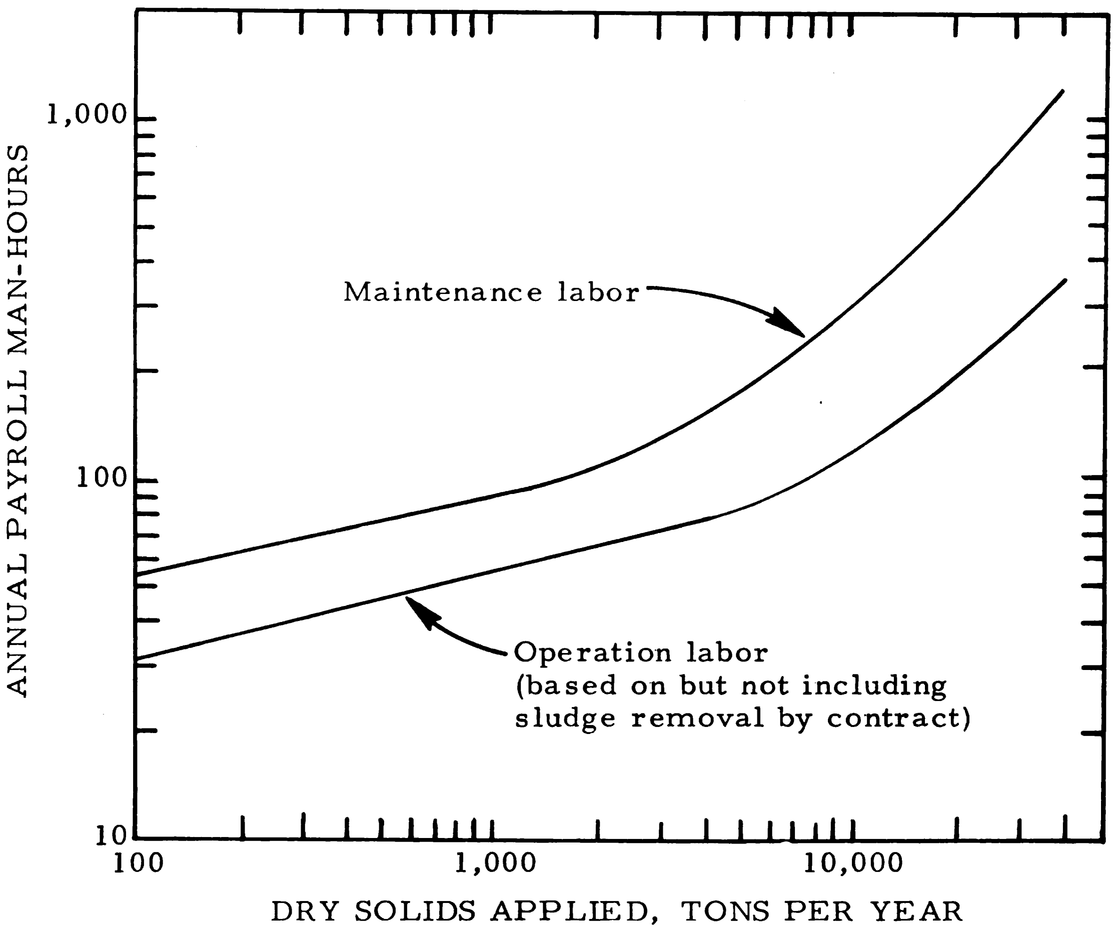


Figure 12. Sludge lagoon labor requirements [11]

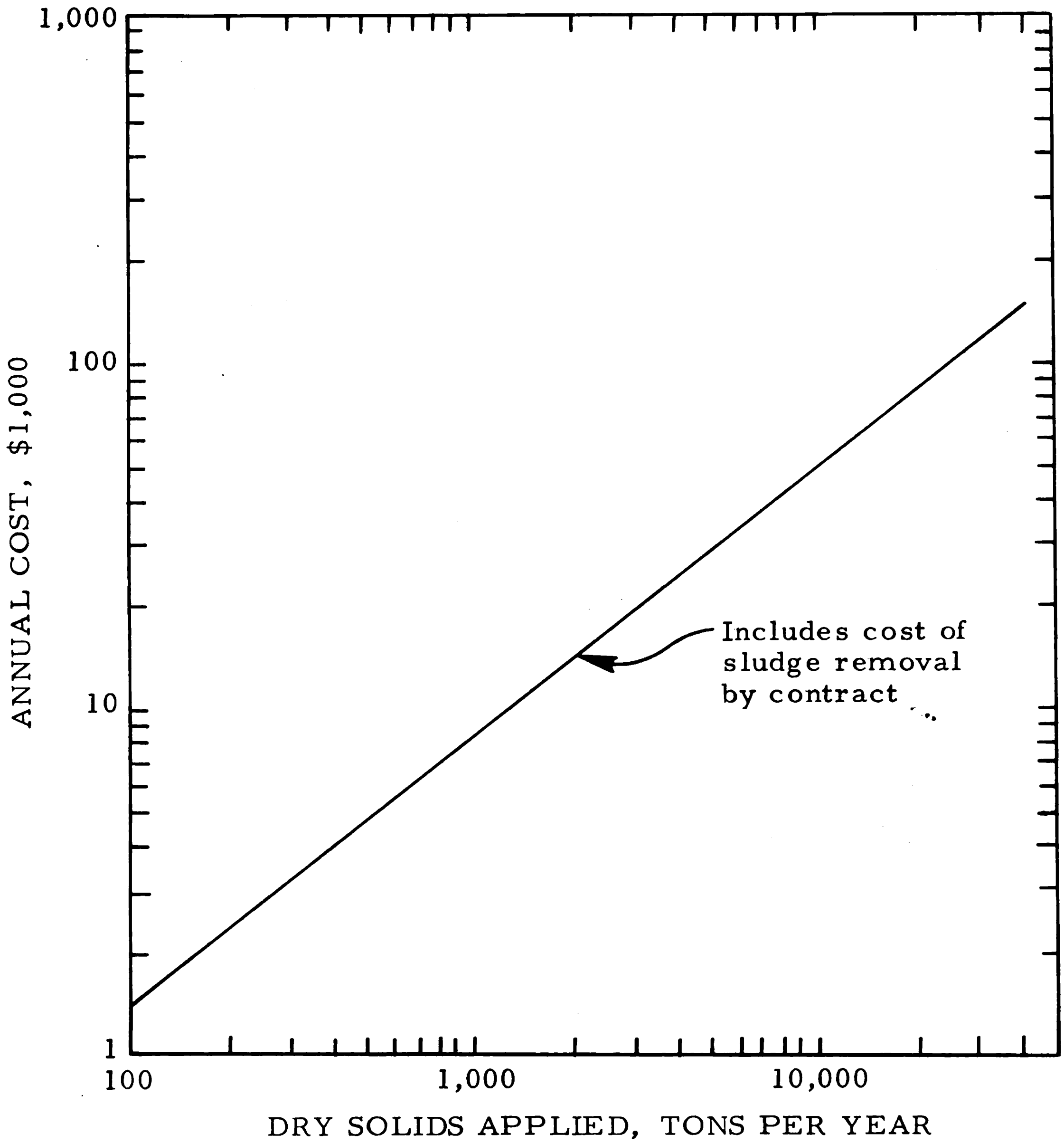


Figure 13. Sludge lagoons material and supply costs [11]

show the labor requirements and supply requirements and how they increase steadily as the volume of solids handled per year increases.[11]

The energy requirements of the sludge lagoon are very small as it uses power only for pumping; no heating, aeration, or coverings are required. Costs and power are kept at a minimum with the only major disadvantage being the time required to hold the sludge. It ranges anywhere from 3 to 5 years.[11]

CONDITIONING

Conditioning is the pretreatment of sludge to facilitate dewatering. Two basic types of conditioning are chemical and physical. Chemical conditioning can use both organic and inorganic chemicals and physical conditioning can be accomplished using freezing or heat treatment.

Chemical conditioning is a coagulation and flocculation process. Inorganic chemicals such as ferric chloride, lime and aluminum sulfate, as well as organic polyelectrolytes, primarily the cationic and anionic polymers, have been effective in reducing the resistance to dewatering of the sludges.[2] The polyelectrolytes increase the dewatering rate more than inorganic chemicals, but the cost of the polyelectrolytes is very high. Table 7 presents the daily cost of chemicals for conditioning.

TABLE 7

CHEMICAL COSTS

Chemical	Avg. Dose (mg/l)	Flow (MGD)	Cost ($/day)	Usage (lb/day)	Daily Cost
Ferric Chloride	110.0	4	0.066	918.0	242.36
Cationic Polymer	1.35	4	1.45	11.3	65.56
Anionic Polymer	0.75	4	1.35	6.25	33.76

If chemical conditioning is used, the capital, operating and maintenance costs will be the same regardless of type of chemical. The only choice affecting costs is in the type of chemicals used. There are many conditioning chemicals from which to choose.

Freezing is a very unusual process to be used in sewage treatment but it is a very effective sludge conditioner.[3] Costs of this process are very high and include power, flocculants (if needed), and expensive refrigerating fluids. It takes about 170 BTU's to freeze one pound of sludge.[3]

Capital costs of the freezing process include tanks, stirrers, buildings, automatic controls and the freezing plant.[13] Capital costs vary about a mean of $ 17,000 per 1000 gallons of sludge processed.[14] Operating costs are in the range of $4.75 to $49.50 per 1000 gallons depending on the type of sludge.[3-14-15] The power required for this process is very high ranging from 180 to 230 KWH per 1000 gallons.[14]

Very high operating costs and energy requirements have been the major factors in keeping freezing from becoming a widely used process. This process would be very effective in a cold climate.

On the opposite end of the scale, heat treatment uses temperatures between 300 and 500 degrees F and pressures of 150 to 400 psig[5] to condition sludge. Heat treatment improves the dewaterability of sludges ten times better than chemical conditioning. It also has the advantages of having no odors, not requiring chemicals and reducing the pathogens to zero.[3]

The wet oxidation process operated at low pressures can be used for heat treatment. The operating costs would be less than wet oxidation due to lower pressures and temperatures. Power requirements are high because of the higher than normal temperatures and pressures. Table 8 shows the operating costs for thermal conditioning in Kalamazoo, Michigan.[16]

TABLE 8

THERMAL SLUDGE CONDITIONING

ITEMS	ACTUAL COSTS	PREDICTED COSTS
Maintenance	$ 3.12/MG	$ 2.00/MG
Power*	$ 1.41/MG	$ 1.00/MG
Fuel**	$ 1.27/MG	$ 2.20/MG

*electrical rate = $ 0.01/KWH
** fuel costs = $ 1.0/million BTU

DEWATERING

Sludge conditioning by either a chemical or physical conditioner is used primarily with the dewatering step of sludge treatment. The primary objective of dewatering is to reduce the sludge moisture content to a degree allowing ultimate disposal. The main methods of dewatering consist of vacuum filteration, centrifugation, pressure filtration and sand bed drying. Table 9 shows the relationship of dewatering to other sludge treatment processes for typical municipal sludges.[5]

TABLE 9

	Pretreatment		Normal Use of Sludge Cake			
Method	Thicken	Condition	Land Fill	Land Spread	Heat Drying	Inciner-ation
Vac. Filter	yes	yes	yes	yes	yes	yes
Centrifuge	yes	yes	yes	yes	yes	yes
Filt. Press	yes	yes	yes	variable	no	yes
Drying Bed	variable	no	yes	yes	no	no

Capital and construction costs of vacuum vilters, associated equipment and structures are related to the filter surface area. The filters themselves cost $95.00 to $275.00 per square foot.[3] The buildings usually double the cost. An equation developed by Dorr-Oliver shows the relation between costs and filter area. The equationis:[10]

$$\text{LOG(COST)} = 0.65 - 0.66(\text{LOG(A)})$$

where COST = hundred dollars per ft^2 and A = area in 100 square feet.

Equipment used in vacuum filters includes the filter, vacuum receiver, vacuum pump, filtrate pump, chemical feed tanks, sludge pump and sludge flocculator. Table 10 shows capital costs of vacuum filters with their respective building areas.[15]

TABLE 10

VACUUM FILTER COSTS (1972)

Type	Size	Filter Cost	Bldg* Cost	Const** Cost	Total Cost
Rotary	10'dia-17'face	58100	6000	20700	85,800
Convent.	6' " - 6' "	30000	3000	10500	43,500
Rotary	10' " -14' "	53500	5000	18600	76,600

*assumed to be $ 10.00 per sq. ft. of building
** assumed to be 35% of the equipment cost

Figure 14 shows the steady rise in construction costs as the size of filter increases.[11] Operation and maintenance costs depend on chemicals (49%), direct labor (20%), supervisory and maintenance labor (20%), power (9%) and supplies (2%).[17] Power costs are directly proportional to the filter area. This is shown in the following equation:[10]

COST = 0.15 (A) where A = area in sq. ft. and COST = cents per hour (includes power cost of 1.5¢ per KWH)

The labor required for operation and maintenance of the vacuum filter are shown in Figure 15. The operational labor for hauling the sludge to a landfill is higher than that of conveying the sludge to an incinerator.[11]

Centrifugation has some advantages over vacuum filtration. It is simple, compact, totally enclosed, flexible, and costs are moderate.[3] Centrifugation uses less power and requires less maintenance than vacuum filters.

Capital costs of centrifuges vary with the size of centrifuge purchased, which is dependent on the flow. Table 11 shows the capital costs of the Sharples SP-6500‡ centrifuges together with the building requirements and construction costs.[15]

‡mentioned product does not imply endorsement

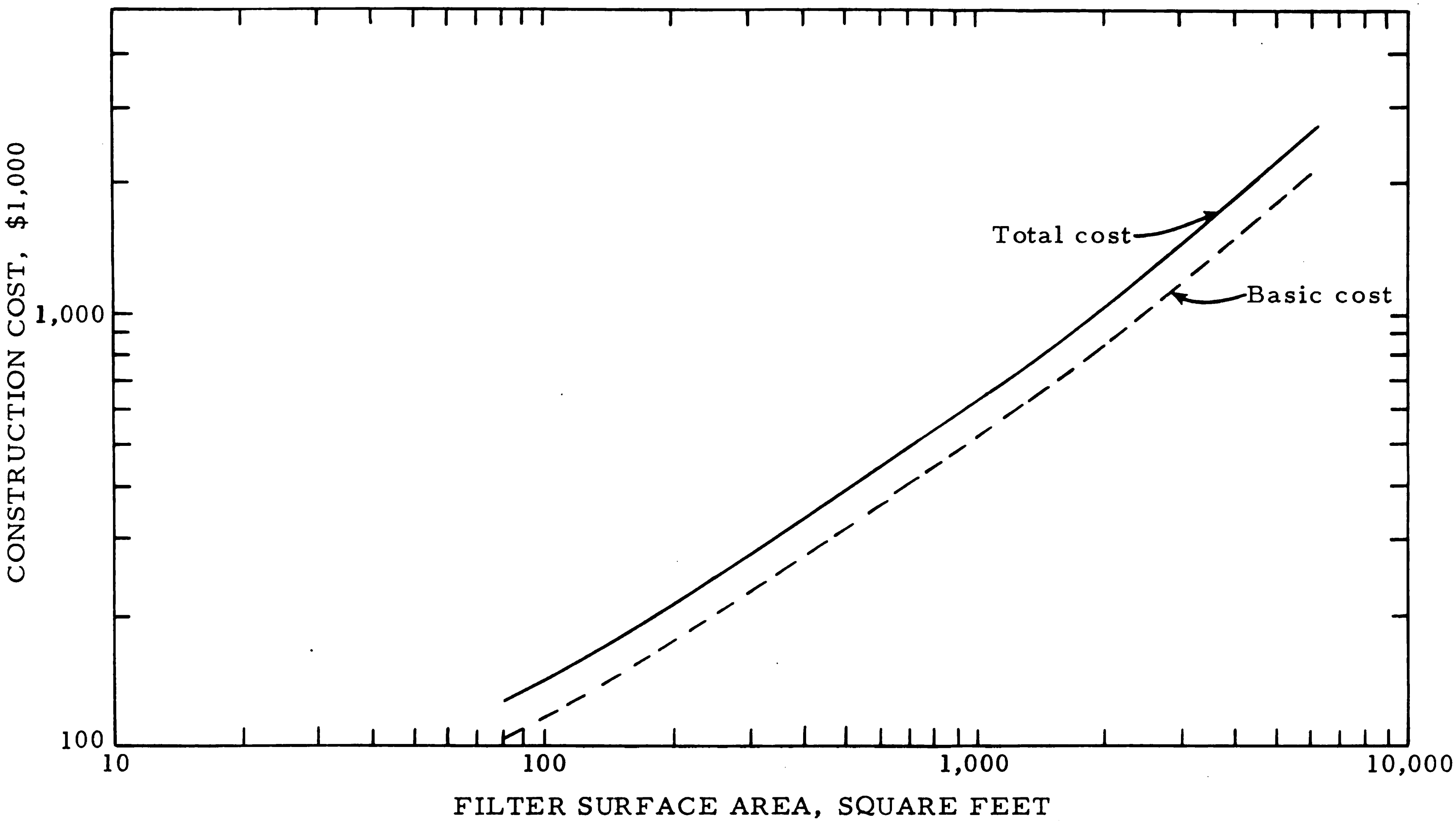


Figure 14. Vacuum filter construction costs [11]

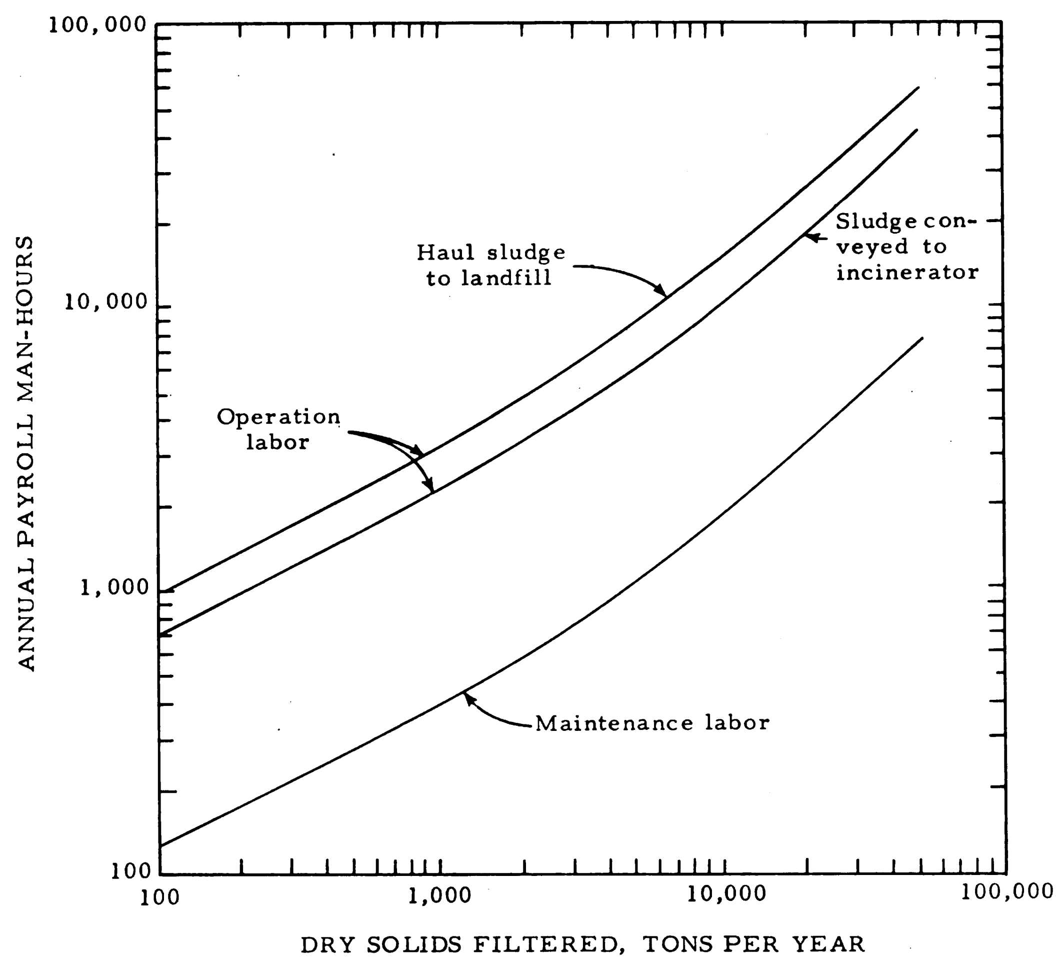


Figure 15. Vacuum filtration labor requirements [11]

TABLE 11

CENTRIFUGE COSTS (1972)

No. of Units	Unit Cost($)	Bldg* Cost($)	Const** Cost($)	Total Cost
5	55,000	10,000	96,300	381,300
10	55,000	20,000	192,500	762,500
2	55,000	4,000	38,500	152,500

*assumed to be $ 10.00 per sq. ft.
** assumed to be 35% of the equipment cost

The capital cost of $ 55,000 per unit remains constant, and the construction costs and building size required are directly proportional to the number of centrifuges employed. The equation developed by Dorr-Oliver for the capital cost of centrifuges is:[10]

LOG(COST) = 2.5 - 0.193LOG(I.F.)

where COST = dollars per pound and I.F. = influent flow in lb dry solids/hour.

This equation involves only the cost of the centrifuges and does not include any accessories or construction costs. Figure 16 shows how the construction costs of centrifugation increases as the capacity increases.[11]

O and M costs depend on the power used, the chemicals used, and the amount of labor required. Table 12 shows the operating cost in terms of maintenance, operating labor, energy, amortization and chemicals.

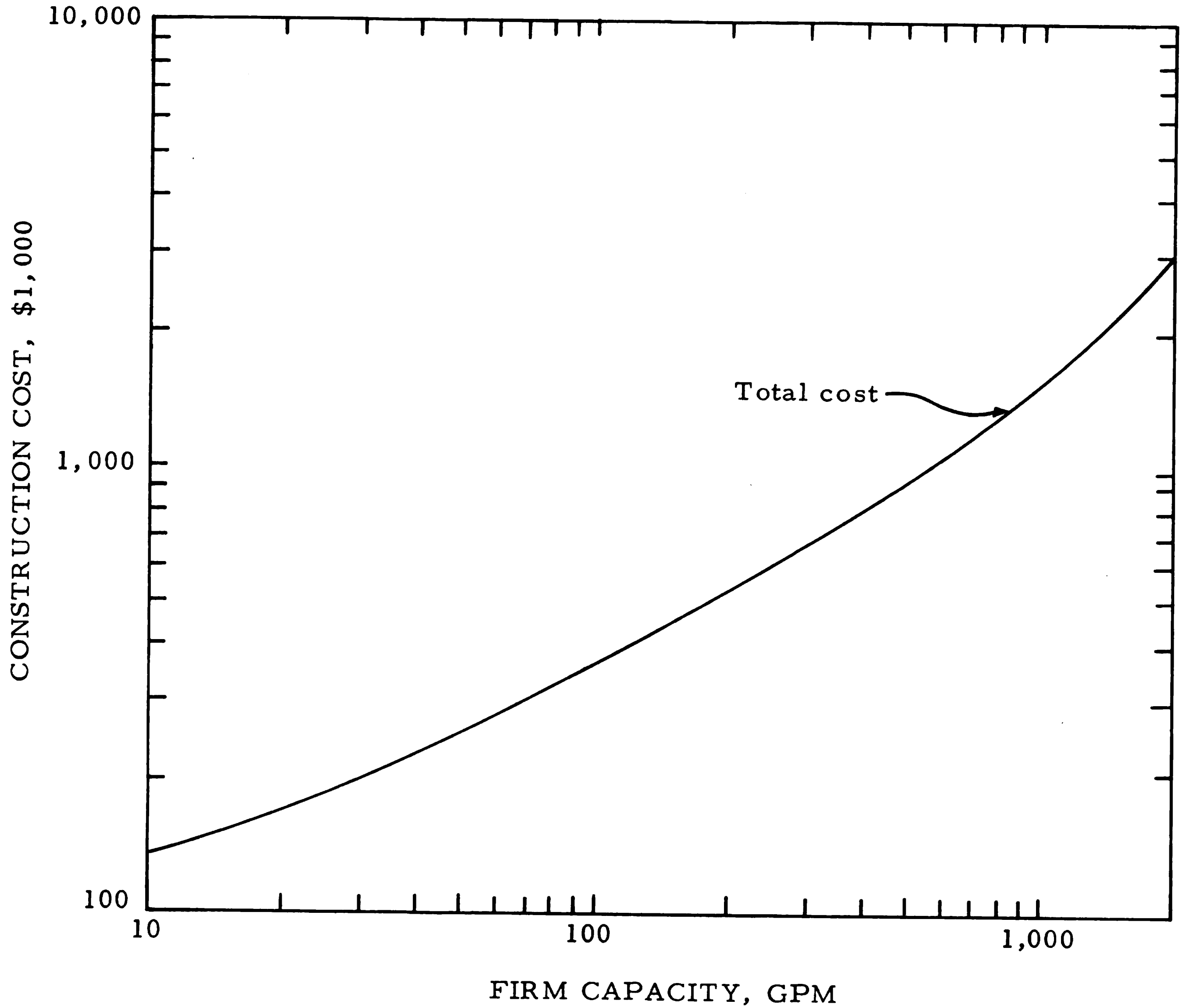


Figure 16. Centrifugation construction costs [11]

TABLE 12

CENTRIFUGE PERFORMANCE AND OPERATING COST

Plant Flow (MGD)	No. of Units	Mach. Size (IN)	Op. Hrs /wk	Maint. ($) ton	Labor ($) ton	Energy ($) ton	Amort* ($) ton	Total** ($) ton
18	1	24-38	168	2.53	2.71	0.70	1.30	16.54
5	1	24-38	9	1.75	0.94	0.39	13.20	16.28
3.8	1	24-60	21	2.63	7.17	0.49	7.65	30.74
8	2	24-38	35	1.74	1.00	0.35	3.23	6.32
45	2	24-60	60	1.90	2.50	1.39	7.65	13.44
6	2	18-42	48	2.73	1.53	0.59	4.32	14.89
1.5	1	18-42	7.5	0.97	7.40	1.33	71.70	92.60
1.7	1	18-42	30	1.36	9.00	1.58	20.30	44.55
1.2	1	24-38	3	0.24	12.70	0.83	100.00	113.77
20	3	24-60	40	2.16	1.05	0.31	3.10	14.62
7	1	24-60	40	3.66	3.20	0.70	5.50	17.62
7.5	2	24-60	168	4.32	3.26	1.65	3.65	26.88

*amortization based on 6% interest over 25 years
** includes chemicals at various costs and various dosages

As shown in Table 12, the components of the operating costs vary with flow and hours of operation per week. Small plants running for just a few hours a week spend more money on the process than do the larger plants.

The power requirements of a centrifuge depend on the bowl size and the speed at which the machine is run. Table 13 shows the power used in centrifugation in relation to plant flow.[6]

TABLE 13

CENTRIFUGE POWER REQUIREMENTS

Plant Size (MGD)	Power Needed (KWH/day) Primary	Activated
1	28.0	90.0
10	256.0	435.0
100	1400.0	4348.0

Centrifuges use approximately the same amount of power that vacuum filters use.

The labor requirements of centrifugation depend on the service required to operate and maintain the high solids removal characteristics. Figure 17 shows the annual payroll hours needed for maintenance and operating labor.[11] The operational labor is more than maintenance and is about the same as the labor requirements of vacuum filtration.

Over six thousand wastewater treatment plants in the United States use the method of sand drying beds for dewatering sludges.[3] These plants, however, are older plants and the drying beds are becoming obsolete as plants become larger and new dewatering techniques are developed.

Construction costs are related to surface area requirements which depend on the quantity and quality of sludge, local climate, and whether or not the beds will be covered.[11] Figure 18 presents the construction costs of twenty-two actual uncovered drying bed installations.[11] The cost rises with increasing surface area. The capital cost of the beds can double if mechanical lifting and conveying equipment is employed.

The O and M costs of drying beds are primarily due to the loading and hauling of the dried sludge, and keeping the beds in proper operating condition. Operating costs have been determined to range between $ 1.00 and $ 10.00 per ton of dry solids.[3] The wide range is due to the different techniques of loading and unloading the sludge from the bed.

The labor required to keep the drying beds operational is shown in Figure 19.[11] The required operational labor is more than the maintenance labor due to the loading and unloading technique used.

The last method of dewatering in use today is pressure filtration or filter presses. Pressure filtration is a batch process and requires a great deal of labor, but it produces higher solids concentration and reduced chemical consumption.

Capital costs of pressure filters vary with size of filter used. Cost of the filters includes the cost of presses, plate shifters, feed pumps, precoat equipment, buildings, and installation. Table 14 presents the cost breakdown of four pressure filters in Virginia, 1972.[15]

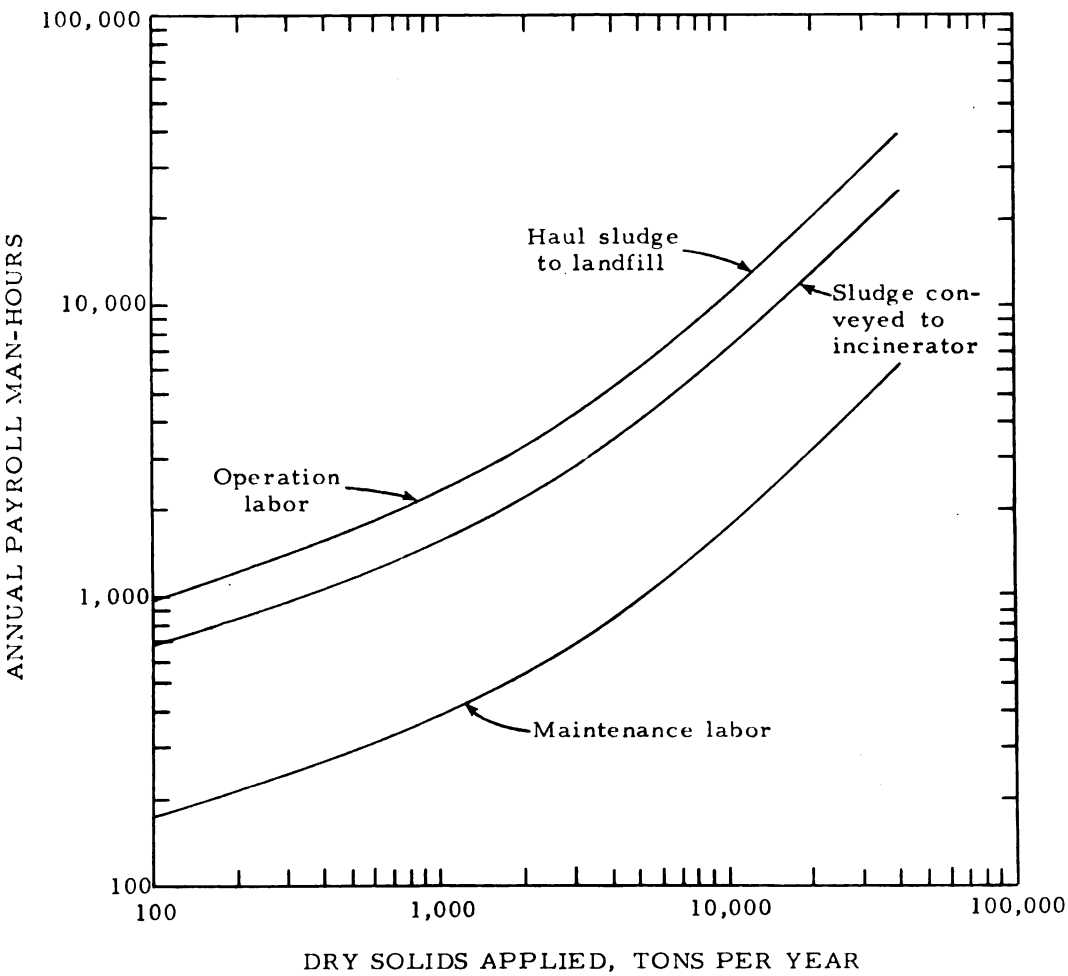


Figure 17. Centrifugation labor requirements [11]

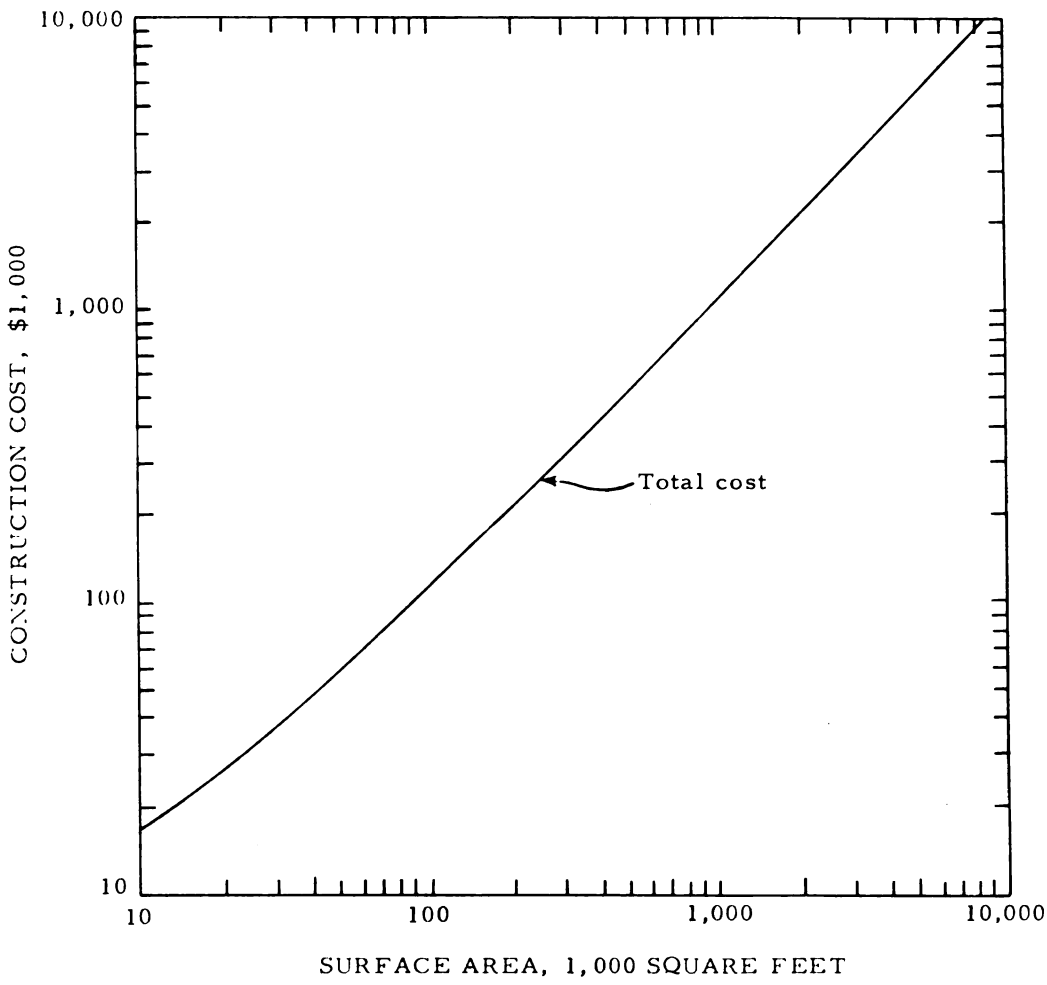


Figure 18. Drying beds construction cost [11]

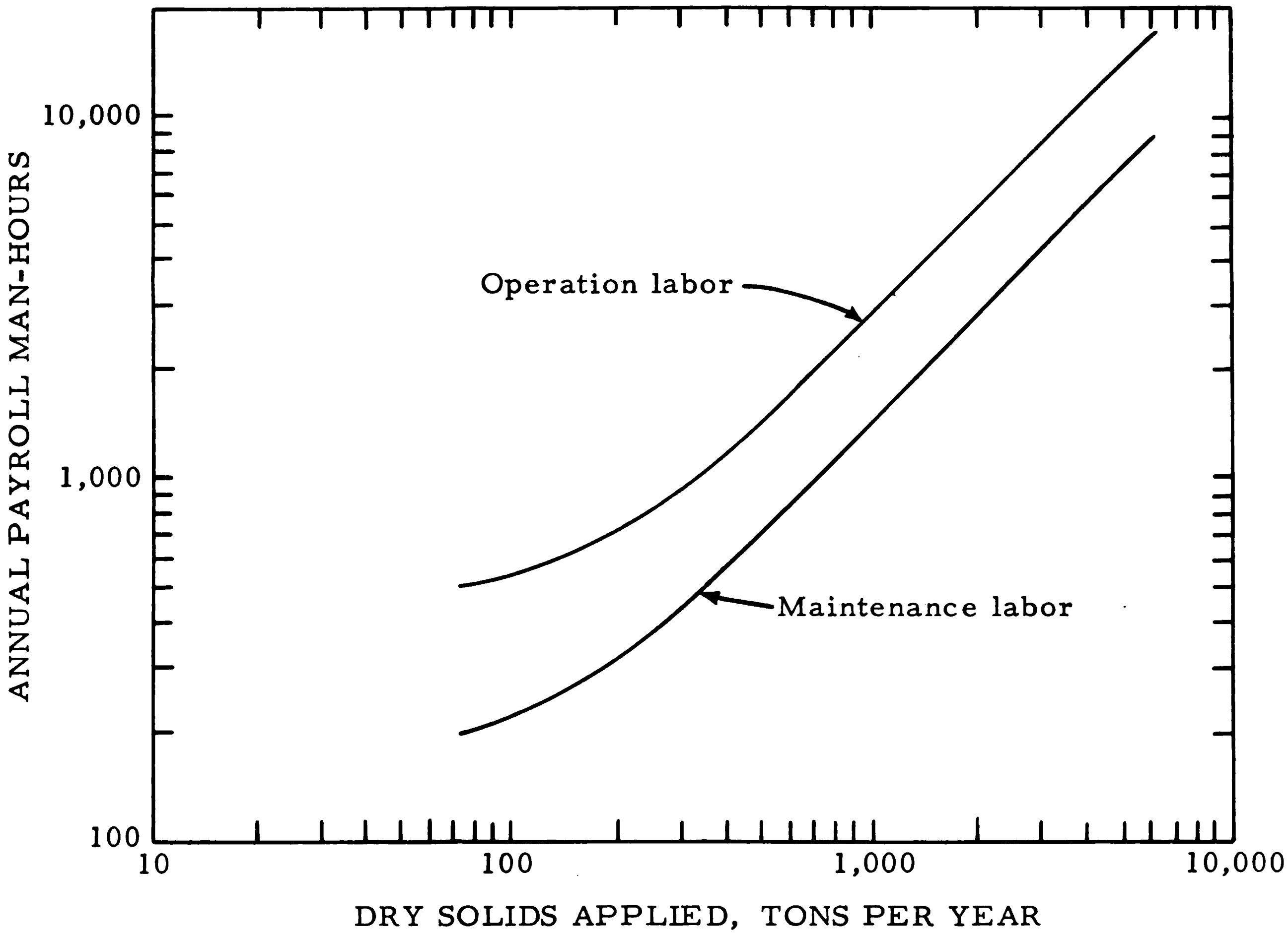


Figure 19. Sludge drying beds labor requirements [11]

TABLE 14

PRESSURE FILTER COSTS

No. of Units	Size (In.)	Bldg Area	Cost (X1000 $) Press	Shift	Prect	Bldg*	Inst**	Total***
4	48	3200	80	9.6	20	32	38.7	181.2
3	48	2100	69	6.9	15	21	32.1	144.9
1	48	1200	21	2.7	5	12	10.4	52.0
3	48	18000	67.5	6.6	18	18	31.5	139.5

*based on $ 10.00/sq. ft.
** based on 35% of total equipment
*** includes a $900.00 feed pump

The initial cost of the filters ranges between $20,000 and $22,500 each and the total costs vary accordingly.[15]

Operating cost of pressure filters depends on the labor required (about 2 men per filter), the chemicals required, and the power used (about 270 KWH/day for a 48" filter). Operating costs without chemicals have been determined to be about $4.69/ton, and the chemicals add another $7.29/ton.[5] Using chemicals with filter presses increases the solids recovery, with a consequent increase in the solids concentration.

REDUCTION

Sludge reduction processes are thermal processes. They provide a major reduction in the sludge solids. Common established processes of reduction are incineration and the wet-air oxidation, or Zimpro*, process.

Sludge incineration is generally more expensive than other sludge disposal methods. The capital cost of incineration systems depends on the type of incinerator, and whether or not pollution control equipment is required. If the deoderizer is installed with the incinerator, the capital cost increases about 3%, and the operating cost increases about 50%. Table 15 shows the capital costs of incinerators according to manufacturer's 1968 prices.[19]

*mentioned product does not imply endorsement

TABLE 15

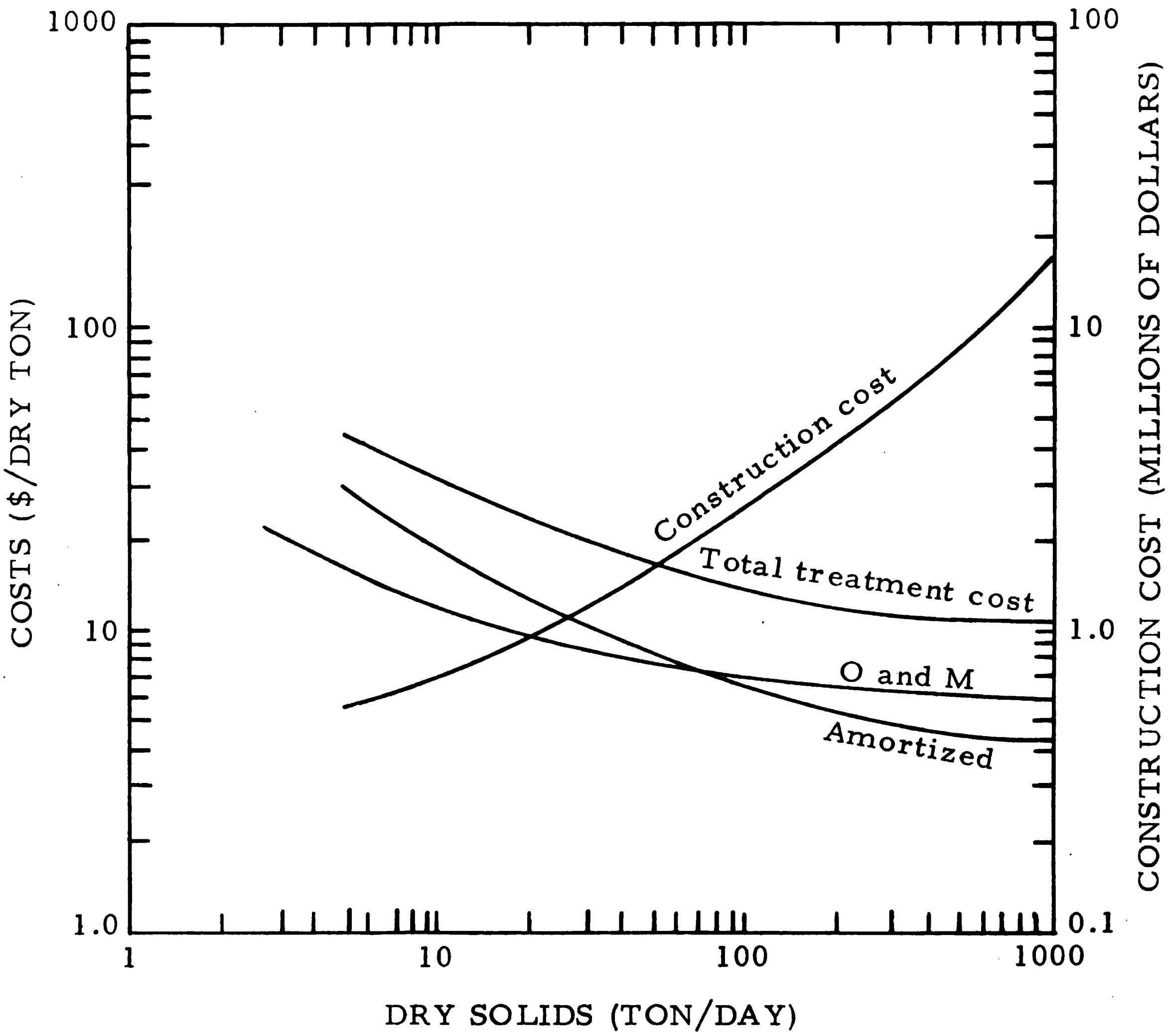
CAPITAL INCINERATOR COSTS

Type	Size (lb/hr)	Cost ($)
Fluid Solid	200	180,000
	400	300,000
	1000	550,000
	2000	825,000
Multiple Hearth	500	300,000
	2000	550,000
	4000	700,000
	6000	850,000
Cyclo-burner	130	70,000

The multiple hearth furnace is the most commonly used incinerator in the United States today, and the prices and sizes show why. The reported operating costs of multiple hearth furnaces vary substantially due to moisture content of the sludge, labor, power and auximilary fuel. Rochester, New York, reports operating costs of $24.55/ton for incineration while South Lake Tahoe reports an operating cost of $12.71 per ton.[5] Figure 20 shows the decreasing costs for operating a multiple hearth furnace as the solids per day increases.[5]

The labor associated with incinerators is included in the operation and maintenance of conveyors, ash handling equipment, control centers and the building enclosing the furnace. Figure 21 shows the annual payroll hours required for incineration as a function of dry solids burned per year.[11]

The power requirements are due to the electrical power and auxiliary fuel needed to maintain adequate temperatures within the furnace. Raw primary sludge with 70% volatile solids has a fuel value of about 7800 BTU/lb of dry solids and will burn without fuel once combustion has started.[20] The auxiliary fuel unit cost decreases as the cake solids concentration from the dewatering process increases. A solids concentration of over 30 to 35% will support combustion without auxiliary fuel. Figure 22 shows the annual cost of electrical power and fuel cost for an incinerator.



Notes:

1. Minneapolis. Mar. 1972. ENR Construction Cost Index of 1827.
2. Amortization at 7% for 20 years.
3. Labor rate of $6.25 per hour.
4. Exhaust gas scrubber and enclosing structure included.
5. Costs do not include deodorization of gases: where required, add $4 to $10/dry ton.

Figure 20. Multiple hearth incineration costs [5]

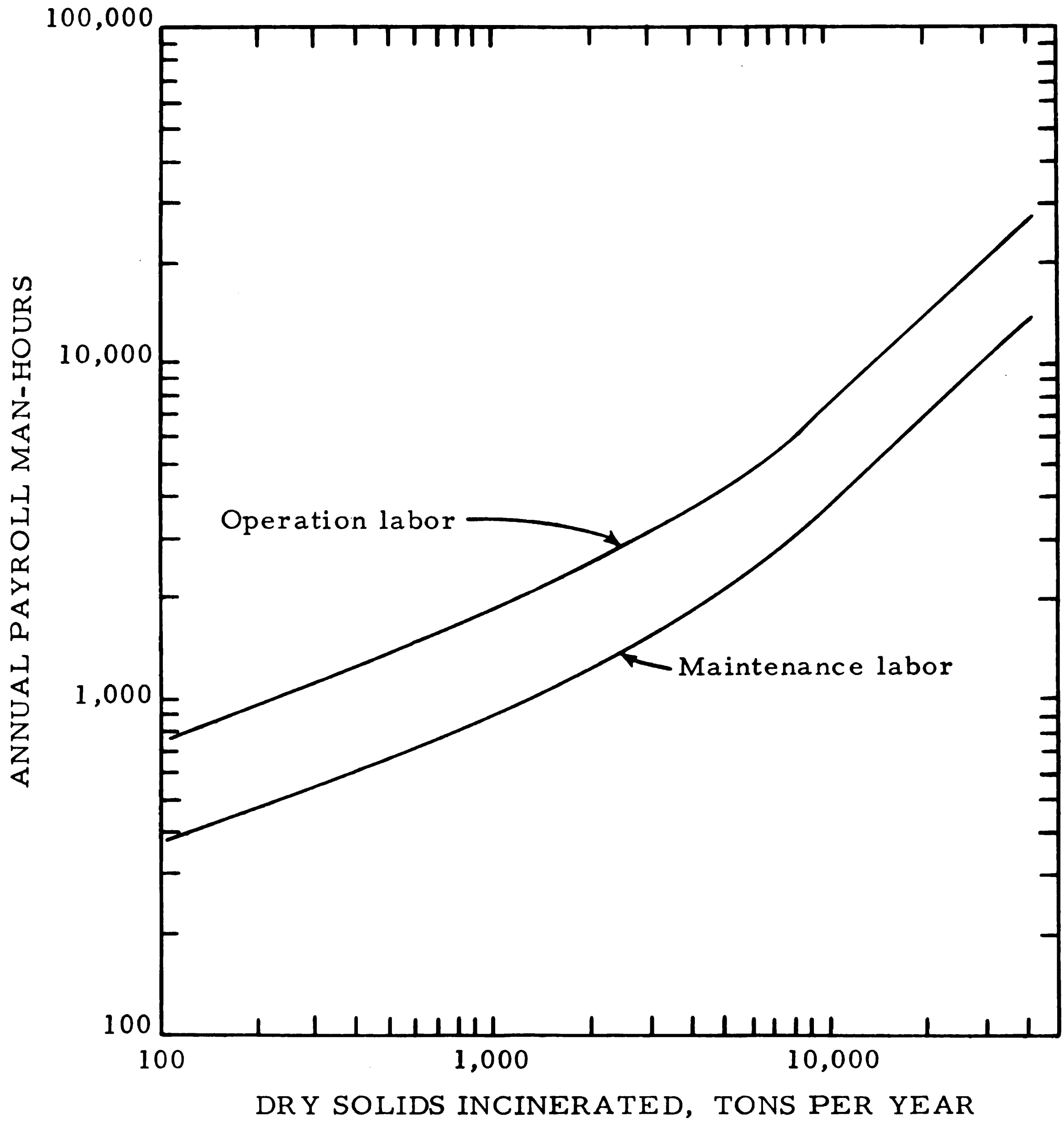


Figure 21. Incineration labor requirements [11]

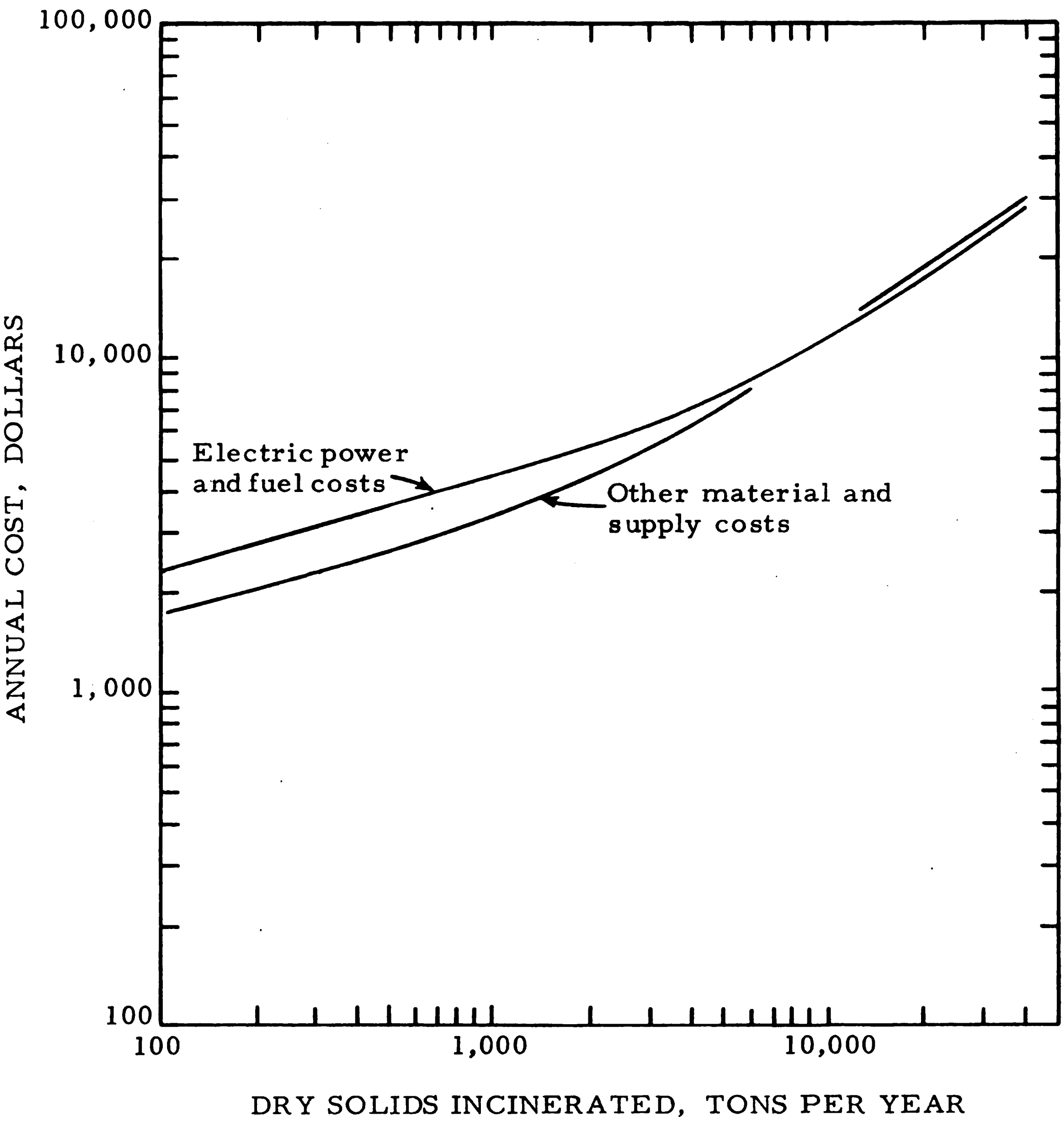


Figure 22. Incineration material and supply costs [11]

Operating costs for fluidized bed incinerators have been estimated by the East Cliff Sanitary District, California. The costs were reported to be \$25.32 per ton which includes \$2.50 per ton for fuel, \$4.47 per ton for power and \$18.35 per ton for labor.[3]

Wet-air oxidation refers to the oxidation of sludge solids in water by applying heat and pressure. Basic equipment is a reactor, air compressor, heat exchanger, and a high pressure sludge pump.[3] The process can be run at both high and low pressures, with the high pressure costing more. The economy of both processes depends on recovery of heat.

Figure 23 shows the installed cost and the operating cost of the high pressure oxidation (HPO) system as a function of the capacity.[21] Figure 24 shows the same costs for a low pressure oxidation (LPO) process.[21] The installed cost for the HPO system is 4 to 5 times the installed cost of the LPO system. The operating cost of HPO is double the operating costs of LPO. HPO costs more, but it reduces twice the volume of insoluble volatiles than the LPO system.

At Wheeling, West Virginia, in 1965 a 5.6 ton/day Zimpro process was installed for \$284,000. The operating costs were found to be about \$19.90 per ton processed. This includes power at \$6.11/ton (31%), chemicals at \$4.13/ton (21%), fuel at \$1.65/ton (8%), maintenance at \$1.17/ton (6%) and labor at \$6.91/ton (34%).[3-5] Power and labor are quite high in this process and make it uninviting to an energy minded community.

FINAL DISPOSAL

No matter what thickening, stabilization, conditioning, dewatering, or combustion process is employed, provision must be made to dispose of the inevitable end product. Common methods of final disposal include land spreading for fertilizer or soil conditioning, lagooning and landfilling.

Using dewatered, digested sludge as a fertilizer and soil conditioner is becoming a popular alternative to combustion and landfill. The best sludge to be used for fertilizer is waste activated sludge that has been vacuum filtered and heat dried. The high nitrogen content of the sludge has not been destroyed by digestion. Prices for nitrogen,

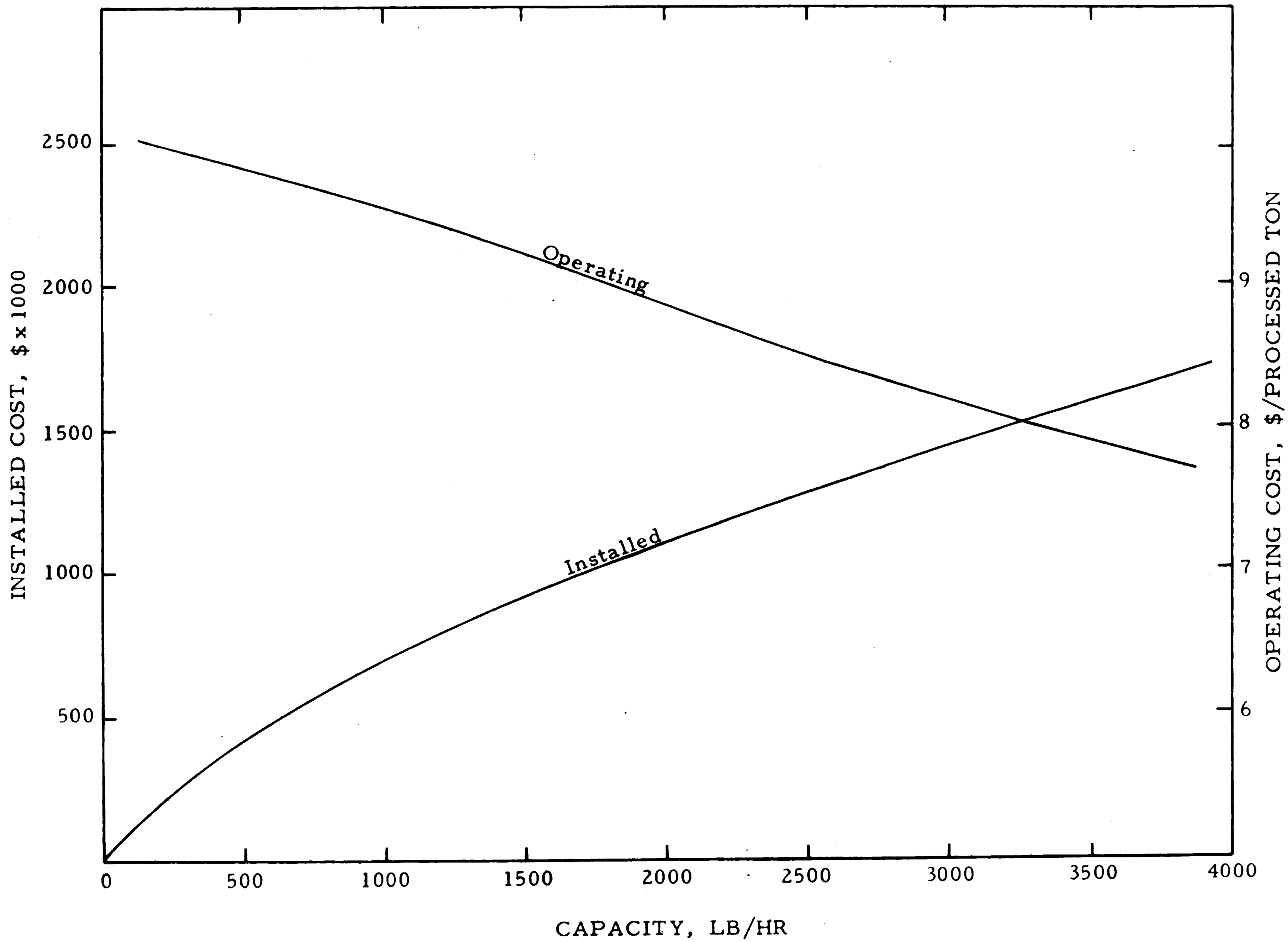


Figure 23. High pressure oxidation costs [21]

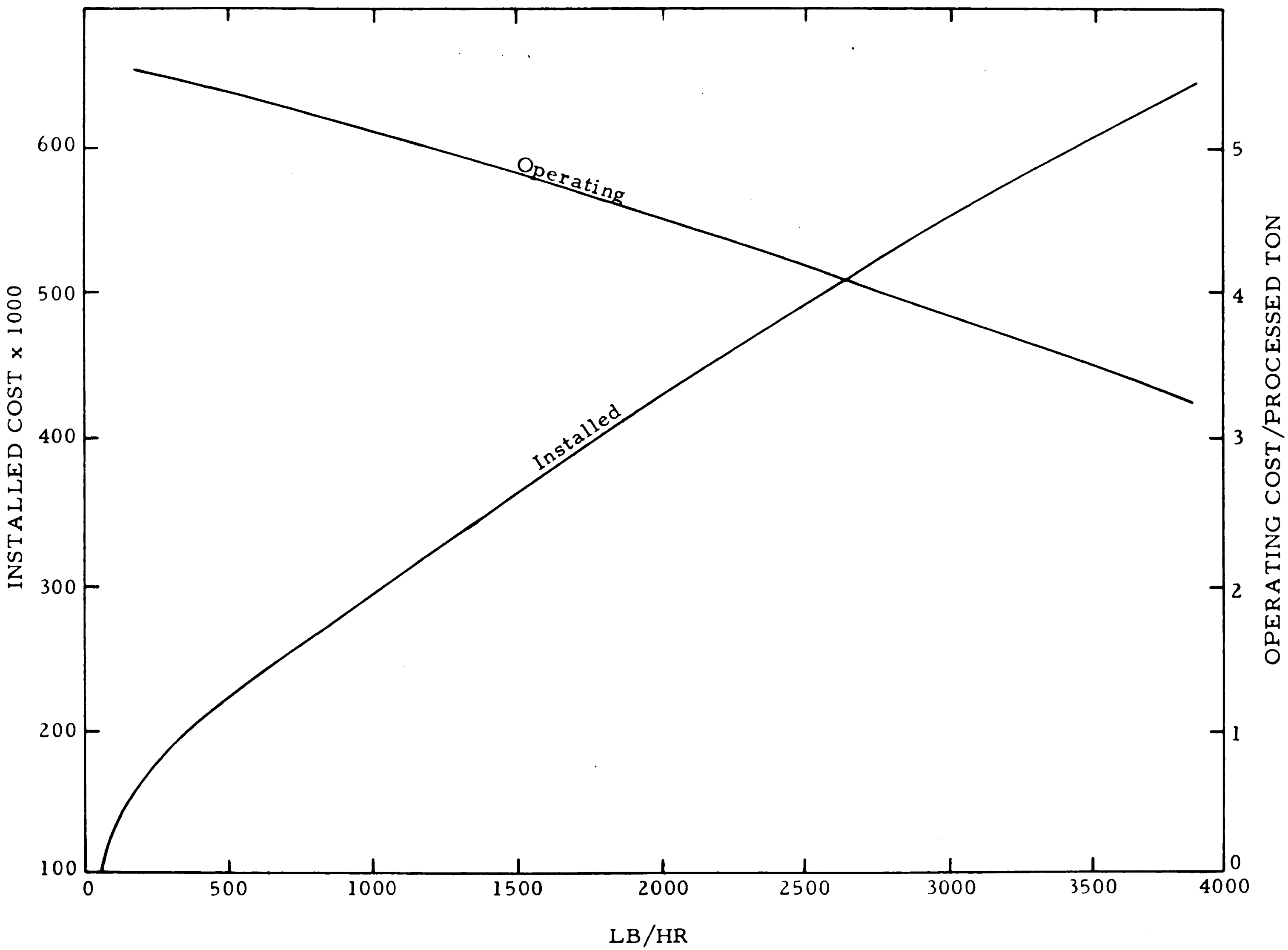


Figure 24. Low pressure oxidation costs [21]

phosphorus, and potash in 1968 were 20 ¢, 10 ¢, and 5 ¢ per lb, respectively. This makes the activated sludge worth $ 20.00/ton, and digested primary sludge worth $ 11.00/ton.[3] The only cost involved in using sludge as a fertilizer is hauling to the farmland.

Various locations around the country are using the land for final disposal of sludge. Table 16 shows various cities that spread sludge on the soil for many reasons and the costs that they incur during the process.[22]

TABLE 16

LAND SPREADING OF SLUDGES

Location	Plant Size (MGD)	Cost ($ /Ton)
New York City	---	11.89
Chicago	1300	26.02
San Diego	90	10.57
St. Marys, Pa.	1.3	19.92
Little Miami, Ohio	1.3	22.00
Piqua, Ohio	3.8	17.5 to 30.00
Franklin, Ohio	4.5	5.00

If there is not a market for sludge then it can be sent to lagoons. The area required for lagoons requires from 1.0 sq. ft. per capita with primary digested sludge in an arid climate, to as high as 4 sq. ft. per capita for activated sludge plants in rainy areas.[23] The operating and capital cost of the lagoons depends on the method of transportation used. Figure 25 shows the transportation cost for liquid organic sludges as a function of distance to the disposal site.[5] A pipeline has lower costs from 40 to 200 miles away. Beyond 200 miles, rail shipping becomes cheaper.

If combustion is used then provisions must be made to dispose of the ash that results. Sometimes pressure filters are used in conjunction with incineration so the ash from the furnaces can be used as a precoat for the filter, Ash, and even dewatered sludge, is sometimes dumped into a landfill area mixed with municipal refuse. Figure 26 shows the capital and O and M costs for sanitary landfills excluding

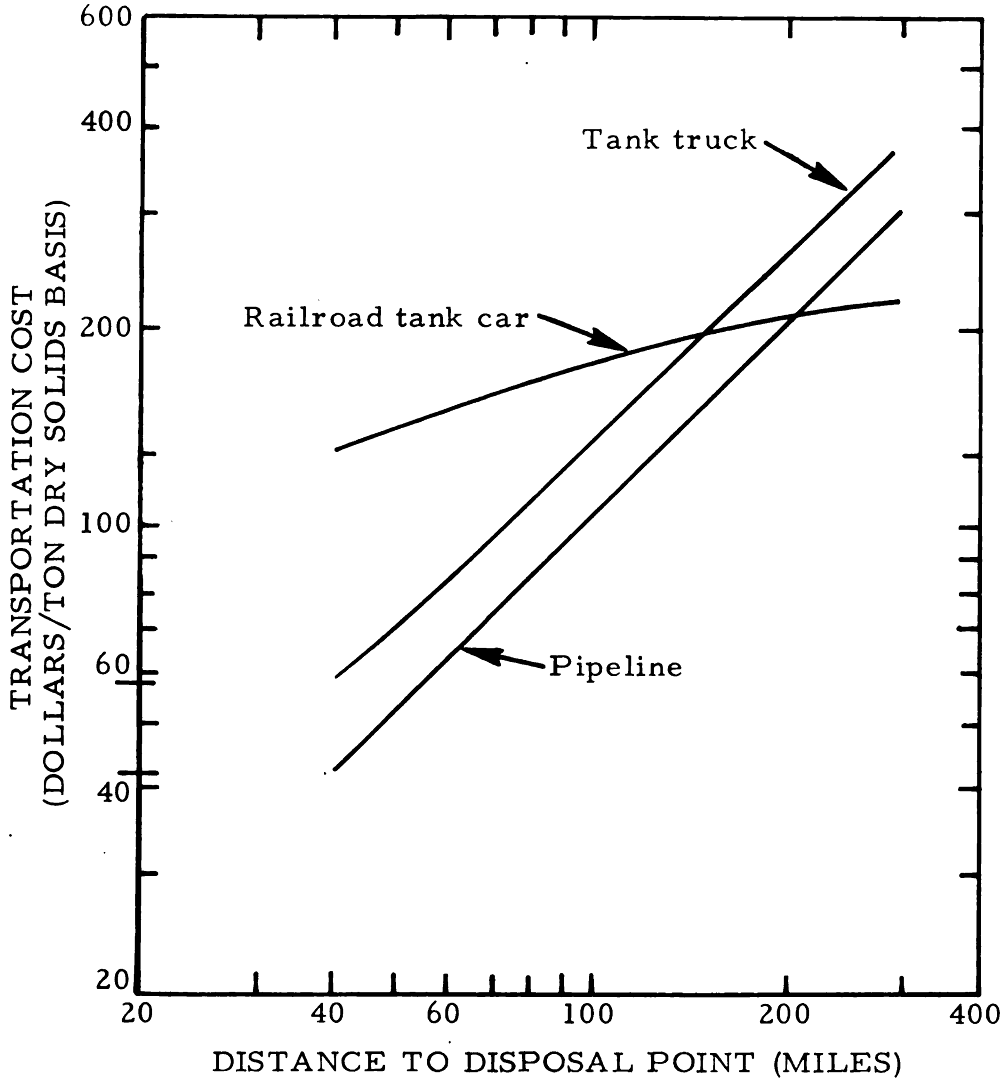
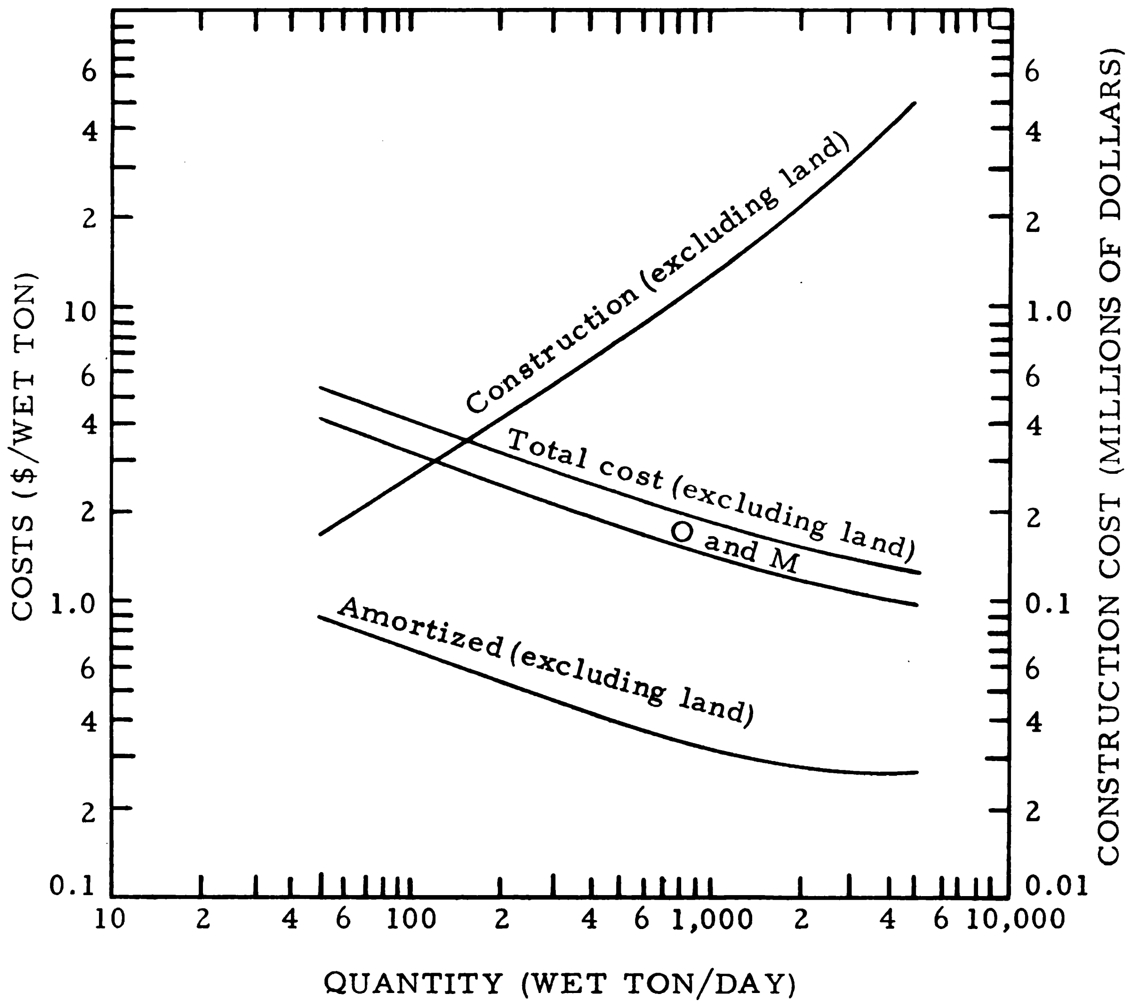


Figure 25. Transportation costs for liquid sludges [5]



Notes:

1. Minneapolis. Mar. 1972. ENR Construction Cost Index of 1872.
2. Amortization of 7% for 20 years.
3. Labor rate of $6.25 per hour.
4. Quantity assumes 6-day work week.
5. Wet sludge must be considered for cost per ton.

Figure 26. Sanitary landfills costs [5]

the cost of the land. The costs are seen to be relatively low and the problems of the landfill are minimal in comparison with other methods.

Ocean disposal of the final sludge product is used by some seacost cities at a very low cost, but environmental legislation has stopped the granting of new ocean disposal facilities until further studies are done.

Capital energy, as defined earlier, has not been found in any of the literature reviewed.

METHODS

The first step in this analysis was the estimation of the amount of mixed primary and activated sludge produced per million gallons of wastewater treated. Each unit process was designed to handle the estimated amount of sludge. Then the amount of materials (steel and concrete) involved in the production or construction of each unit process was determined to calculate the capital energy involved. The capital and operating costs were obtained from values reported in the available literature and together with the capital and operating energy were compared to determine the optimum treatment scheme with regard to energy and costs.

Three sizes of treatment plants were chosen to include most treatment plants in the United States. These sizes are 1.0 MGD, 10.0 MGD, and 100.0 MGD. The wastewater in these plants was assumed to be of typical values for influent biological demand (BOD) and influent suspended solids (SS) are 200 milligrams per liter (mg/l) and 200 mg/l, respectively. Assumptions used in calculating the quantity of sludge are shown in Table 17.[24]

TABLE 17

SLUDGE QUANTITY ASSUMPTIONS

Raw Primary Sludge	
removal efficiency of clarifier ---------	60% SS; 30% BOD
solids concentration ----------	5%
Waste Activated Sludge	
effluent BOD ------ 10% ; solids yield ------	50%
solids concentration ------	0.75%

Each process was designed according to Federal regulations utilizing the estimated sludge generation rates. Table 18 lists the basic criteria followed for each process designed.

TABLE 18

DESIGN PARAMETERS

PROCESS	PARAMETER
Gravity thickener[25-26]	Limiting solids flux rate = 6 lb per sq. ft./day
	Influent solids concentration = 1.3%
	Underflow solids concentration = 6%
	Depth = 15.0 feet
	Wall width = 1.0 feet
Dissolved-air flotation[5]	Solids loading = 2 lb/ft^2/hr
	Solids recovery = 50 to 80%
	Maximum hydraulic loading = 0.80 gpm/sq. ft.
	Volume of sludge = 56 ft^3/million gallons
	Detention time = 30 minutes
Anaerobic digestion[26]	Solids loading = 30 to 100 lb volatiles/1000 cu. ft.
	Detention time = 30 days
	Temperature = 85 to 95 deg. F
	Tank diameter = 20 to 115 feet
	Water depth = 25 feet
	Freeboard = 2.0 feet
	Well insulated covers
	Waste efficiency = 0.75
	Net growth rate = 526 lb/day
Aerobic digestion[26-5]	Detention time = 20 days
	Solids loading = 0.1 to 0.2 lb volatile solids/cu. ft./day

TABLE 18 (continued)

DESIGN PARAMETERS

PROCESS	PARAMETER
Aerobic digestion[26-5] ------	Hydraulic detention time = 20 days
	Air requirements = 25 SCFM/1000 ft^3
	Blower efficiency = 70%
Chemical conditioning[26] ----	Contact time = 30 minutes
	$FeCl_2$ dosage = 2% (raw); 3% (dig.)
	Motor efficiency = 80%
Heat treatment[5-24-26] ----	Pressure = 180 to 210 psig
	Residence time = 30 minutes
	Temperature = 350 to 390 deg. F
Drying beds[26] -------------	Solids loading = 15 $lb/ft^2/yr$
	Open beds in northern climate
	Bed slope = 5%
	Application = 6 to 12 inch layers
	Partitioned into 20 foot wide by 20 to 100 foot long sections
	Loader efficiency = 80%
Vacuum filtration[5-26] ------	Yield = 4 $lb/ft^2/hr$
	Feed solids = 5%
	Effluent solids = 20 to 30%
Centrifugation[19-26] --------	Feed solids = 2%
	Effluent solids = 15 to 40%
	Length/Diameter ratio = 3
	Solids recovery = 80 to 95%
	Bowl speeds = 3000 to 7000 rpm
	Force = 2500 to 6000 G's

TABLE 18 (continued)

PROCESS	PARAMETER
Pressure Filtration[26-28]	Pressure = 60 to 225 psi
	Detention time = 2 hours
	Sludge cake thickness = 1.5"
	Effluent solids = 30 to 50%
	Cake volume = 3.0 ft^3/chamber
	Cake density = 105 lb/cu. ft.
Incineration[6-26]	Solids loading = 2 lb/ft^2/hr
	Temperature = 1400 to 1700 deg. F
	Capacity = 200 to 8000 lb/hr
	Combustibles = 60% of sewage
	Efficiency = 100% of combustibles
Wet oxidation[5]	Pressure = 1000 to 1750 psi
	Temperature = 250 to 700 deg. F
	Detention time = 30 minutes
	Combustibles = 60% of sewage
Fertilizer and Soil[5] Conditioner	Solids loading = 15 tons dry solids per acre/year
	Liquid application rate = 5000 gal/acre/day (MAX)
	Truck working efficiency = 80%
	Hp operating efficiency = 60%
Lagoons[5]	Depth = 5 feet
	Bottom must be 18 inches above water table
	Solids loading = 2.2 lb/ft^3/yr

TABLE 18 (continued)

PROCESS	PARAMETER
Landfill[5] ------------------	Waste layers = 2.0 feet
	Compacted layers = 2.0 feet
Spreading on soil[5] ----------	Same as fertilizer

Once the size of the individual process was determined for all three design flows, the capital costs, operating costs, operating energy and capital energy were determined. Capital costs were taken from data gathered from professional literature and from manufacturers' data. Operating costs were considered to be entirely composed of annual manhours needed for maintenance and operation based on a labor rate of $7.10 per hour for skilled labor.[27] Operating power was calculated as a separate item.

The Sewerage Construction Cost Index (SCCI) determined by the Environmental Protection Agency was used to adjust all capital cost data to a base data of January, 1975. Table 19 shows the Detroit cost index which was used in this study. The base index of 100 is for the period 1957-59.

TABLE 19

S.C.C. INDEX

Year	Detroit
1969	138.7
1970	153.2
1971	163.4
1972	180.7
1973	188.9
1974	200.4
1975	239.6

Power, like money, can be expressed in both operating and capital terms. Capital energy, like capital cost, is the initial amount of energy used to produce a piece of treatment equipment or construct a unit process. In this study capital energy was taken to be the energy required to produce the steel and concrete involved in the equipment or process. This is, of course, only a first approximation as transportation energy and construction energy also contributes to the capital energy.

The total weight of steel and volume of concrete used in the production or construction of a sludge process were used to compute the capital energy for each unit process.

Both operating and capital energy can be expressed in dollars. Once converted to dollars, capital energy can be amortized in the same manner as capital cost at 8% interest over a standard design life of 20 years. In order to make energy costs comparable, it was assumed that all the energy used in the production of the steel and concrete was electrical power. This results in an average dollar value for the capital energy. A local energy cost of $0.03 per KWH was used.

Knowing the operating and capital costs and the operating and capital energy a decision as to the best treatment scheme can be made by applying a sequential decision model known as dynamic programming.[29] Dynamic programming is applicable to the optimization of systems posessing a serial structure with no recycle. Figure 27 shows the framework of sludge handling processes. This flow chart is a typical serial structure with no recycle. For example, whatever happens in the stabilization step influences the events of the dewatering step but has no effect upon the thickening step.

Dynamic programming compares the independent variable of each process with special regard to the limitations and determine the optimum selection for sludge handling. In this work the optimum selection was made for three different assumptions regarding energy and cost for all three design flows mentioned earlier. The conditions used were as follows:

1. Economic optimum - 1975 and future
2. Energy affluent present with energy poor future
3. Energy optimum - 1975 and future

Case one, the economical optimum, was calculated using only operating and capital costs without separation of the energy component. This case assumes that the energy costs will inflate at the same rate as the equipment costs. Case two, the energy poor future, was calculated using 1975 capital costs and considering operating energy in the future. Case three, the energy optimum, was evaluated utilizing only the capital energy and operating energy without consideration of other costs. This leads to a limiting case involving only energy and will be applicable if the energy costs escalate at a faster rate than normal inflation.

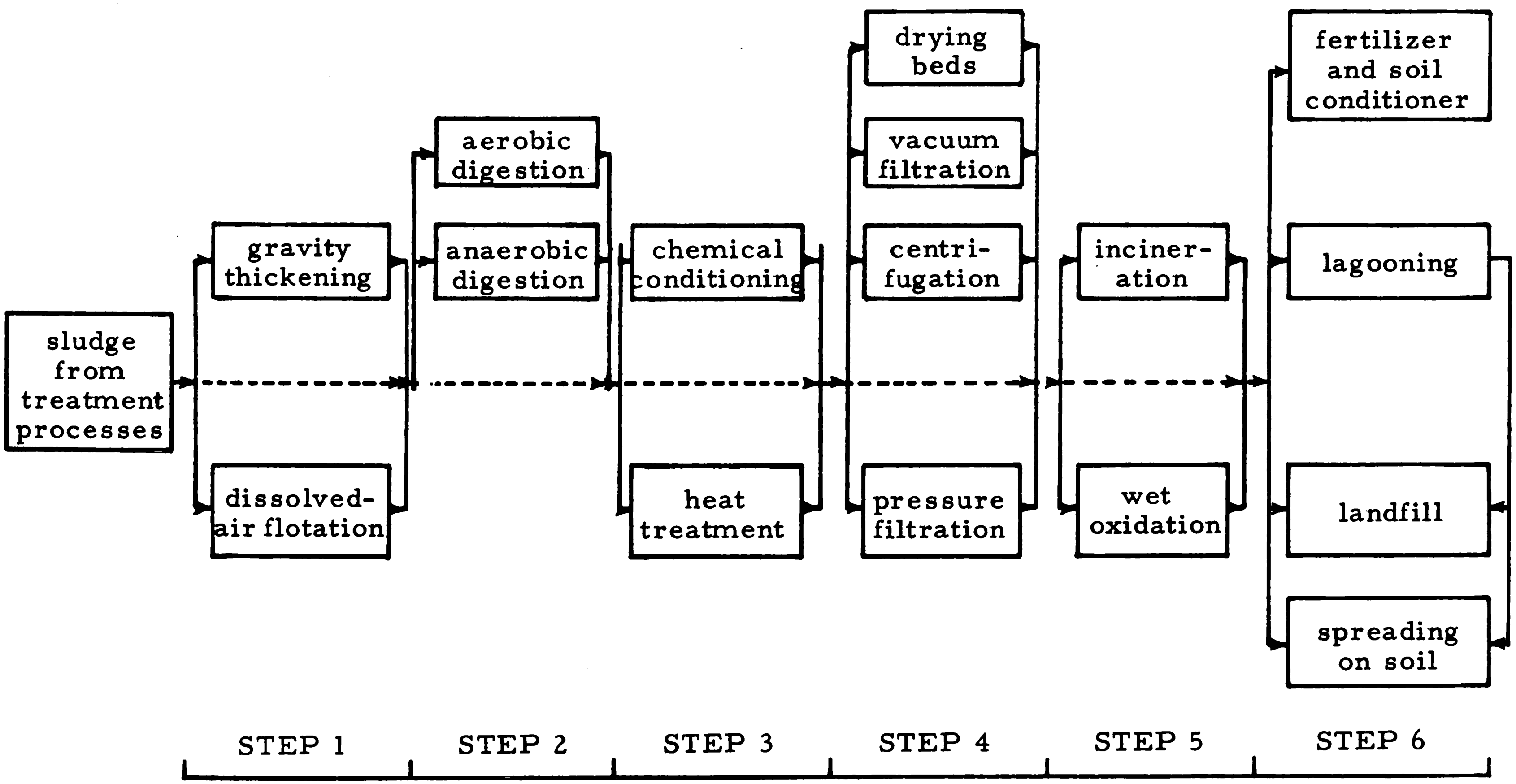


Figure 27. Generalized sludge processing and disposal flowsheet

The three specific cases give an overall view at the sludge handling scheme with regard to the major factors that could affect a choice of treatment, energy and money.

RESULTS

Using the medium value for B.O.D. and S.S., the amount of raw primary sludge was estimated to be 1000 lb per million gallons of wastewater treated. Assuming a 5.0% solids concentration, the volume of primary sludge that must be treated was found to be 2330 gallons per day (gpd). The amount of waste activated sludge produced per million gallons of wastewater treated was calculated to be 1068 lb. Assuming a solids concentration of 0.75%, the volume of sludge was found to be 16,578 gpd. Thus, the total volume of sludge produced per million gallons of wastewater is about 18,908 gallons. Using a specific gravity of 1.03 and a solids concentration of the mixed primary and activated sludge of 1.27%, the amount of sludge solids generated is about 2530 ft^3 per day. (See Appendix A for Calculations).[24] Table 20 shows the amount of raw primary, waste activated and total mixed sludge that has to be handled for the three design flows.

TABLE 20

SLUDGE QUANTITIES

Plant Size (MGD)	Primary (GPD)	Waste Act. (GPD)	Total Sludge (MGD)	Total Sludge (tons/day)
1	2,330	16,578	0.019	1.034
10	23,300	165,780	0.189	10.340
100	233,000	1,657,800	1.891	103.400

The volume of sludge determines the size of the unit process and the size determines the capital cost, capital energy, labor requirements and power needs. These four variables were determined for each stage in the sludge treatment process.

Capital energy is the energy required for materials fabrication. From manufacturing data it was found that the average value of energy used in the production of one ton of finished steel is about 36 million (10^6) B.T.U.[30] It was also determined that one 94 pound bag of cement requires about 175,000 B.T.U.'s to produce.[31] Using a water cement ratio of 0.54 by volume and a concrete composition of 74% aggregate, 3.7% air, 9.3% cement and 13% water, yields an estimated requirement of 2.5 sacks of cement for each cubic yard of concrete. A cubic yard of concrete, therefore, requires about 437,500 B.T.U.'s for production (See Appendix A).

The first step of treatment is thickening using gravity thickeners (GT) and dissolved-air flotation thickeners (DAF). Table 21 shows the power, labor, capital cost and capital energy for both types of thickening. The calculations are shown in Appendix B.

TABLE 21

THICKENING

Plant Size (MGD)	Power (kwh/day) GT	Power (kwh/day) DAF	Labor (hr/yr) GT	Labor (hr/yr) DAF	Cost (1000$) GT	Cost (1000$) DAF	Energy (BTU x 10^6) GT	Energy (BTU x 10^6) DAF
1	10.2	140	220	340	74	23	66	340* N/A**
10	20.4	1216	780	1100	194	257	230	1196* 49**
100	40.8	9384	3600	5000	841	2567	1600	5868* 269**

* if steel tanks are used; ** if concrete tanks are used
N/A signifies that concrete tanks are not applicable here

Table 21 shows that even though gravity thickening uses less energy during operations than the dissolved-air flotation machine, the capital energy required to construct the GT is about five times that of the DAF.

The next step in the sludge handling process is stabilization. Anaerobic digestion (AND) and aerobic digestion (AD) stabilize the sludge to make it less offensive and reduce its volume. Table 22 shows the power, labor, capital cost, and capital energy for the two types of digestion. The calculations are shown in Appendix C.

TABLE 22

STABILIZATION

Plant Size (MGD)	Power (kwh/day)		Labor (hr/yr)		Cost (1000$)		Energy (BTU x 10^6)	
	AND	AD	AND	AD	AND	AD	AND	AD
1	124	233	225	96	222	89	742	57
10	456	2685	1125	480	555	398	5418	390
100	1910	31930	5700	2420	4990	3315	45111	3014

Anaerobic digestion uses less operating power than aerobic digestion but costs more and requires more capital energy.

After digestion the sludge can be conditioned before dewatering. Conditioning usually consists of chemical conditioning (CC) or heat treatment (HT) if there is a market for fertilizer. Table 23 presents the power, labor, capital costs, and capital energy for chemical conditioning and heat treatment. Chemical conditioning is cheaper, uses less operating energy and labor, and requires less capital energy than heat treatment but heat treatment allows for easier dewatering and provides a very useful end product for fertilizer, whereas chemical conditioning does not. See Appendix D for calculations.

TABLE 23

CONDITIONING

Plant Size (MGD)	Power (kwh/day)		Labor (hr/yr)		Cost (x 1000$)		Energy BTU x 10^6	
	CC	HT	CC	HT	CC	HT	CC	HT
1	3	305	1040	520	46	203	29	45
10	80	3050	2600	1300	129	422	324	765
100	917	30500	4368	2190	256	2581	2394	4339

After conditioning the next step is dewatering. Dewatering reduces the volume of the sludge by reducing the water content. The major types of dewatering are drying beds (DB), vacuum filtration (VF), centrifugation (CT) and pressure filtration (PF). Table 24 shows the comparison of the four types of dewatering with respect to the power and labor used in the operation of equipment.

TABLE 24

DEWATERING POWER AND LABOR

Plant Size (MGD)	Power (kwh/day)				Labor (hr/yr)			
	DB	VF	CT	PF	DB	VF	CT	PF
1	90	52	90	62	1750	1640	1370	2080
10	477	531	435	620	17500	5650	4200	5200
100	1551	5208	4400	6204	175000	35500	30000	26208

The power used for dewatering increases greatly as the flow increases except for drying beds which is lower due to the equipment used for removing the dried sludge. The labor requirements for drying beds at the 100.0 MGD plant seem to be quite large. This is due to the use of one man per loader manhour. These values are based on operational data given for the specific equipment.[5]

Another comparison of the four dewatering techniques is shown in Table 25. Capital cost and capital energy are presented with respect to the design flows.

TABLE 25

DEWATERING COSTS AND ENERGY

Plant (MGD)	Costs (x 1000 $)				Energy (BTU x 10^6)			
	DB	VF	CT	PF	DB	VF	CT	PF
1	91	211	422	183	307	180	86	79
10	829	475	844	366	350	510	288	137
100	11302	2638	2536	1468	2526	2727	1134	502

Pressure filters recently have become comparable in price with other dewatering techniques due to vast improvements in filter operations and size in the last few years.[28] See Appendix E for calculations. The high capital costs for the drying beds is due to the large number of machines needed to unload the dried sludge.

Dewatered sludge can be sent directly to disposal or it can be reduced in volume and weight by incineration (INC) or wet oxidation (WO). These two methods are the most common types of reduction used in sludge handling. Incineration produces a dry ash which can be sent to lagoons or to a landfill. Wet oxidation produces a wet ash slurry which usually goes to lagoons but can be used as a soil conditioner or fertilizer. Table 26 shows the power, labor, capital cost and capital energy needed for the use of the reduction step. See Appendix F for the calculations.

TABLE 26

REDUCTION

Plant Size (MGD)	Power (kwh/day) INC	Power (kwh/day) WO	Labor (hr/yr) INC	Labor (hr/yr) WO	Cost (x 1000 $) INC	Cost (x 1000 $) WO	Energy (BTU x 10^6) INC	Energy (BTU x 10^6) WO
1	603	610	1900	520	530	469	601	45
10	1242	6101	5400	1300	928	1408	2558	765
100	4932	61006	39000	2190	2880	6568	14350	4339

The labor requirements are unusually high for incineration because the dry ash cannot be pumped.

Once the sludge is in the smallest volume feasible the sludge is deemed ready for "final disposal". The sludge can be used as a fertilizer and soil conditioner in a digested form (FERT), or sent to a sanitary landfill (LNF) as a dried cake or ash, or sent to permanent lagoons (LAG) in a slurry or as a dried cake. All of these methods require capital costs and labor. Permanent lagoons do not use operating power or capital energy as defined in this report. Table 27 shows the power, labor, capital costs and capital energy requirements of the three basic methods of final disposal. The power involved in using the fertilizer and landfill method is due to the use of heavy equipment. Each process needs many machines to spread the sludge or to bury it. See Appendix G for calculations.

The high labor requirements or final disposal are due to the large volume of sludge that has to be spread. The trucks with larger tanks can not be used because they bog down in the fields so more

TABLE 27

FINAL DISPOSAL

Plant Size (MGD)	Power (kwh/day)			Labor (hr/yr)			Capital Cost (x 1000 $)			Energy (BTU x 10^6)		
	FERT	LAG	LNF	FERT	LAG	LNF	FERT	LAG	LNF	FERT	LAG	LNF
1	2187	---	568	2920	115	2080	22	37	47	180	---	342
10	21874	---	3374	29200	235	5200	220	140	199	1800	---	1152
100	218740	---	14317	292000	1400	8760	2200	660	862	18000	---	1588

smaller tanks must be used and this requires more trucks and labor.

The lagoons and landfills were designed with the idea of using a 25% solids cake for disposal. If the reduction step is used then the costs and power requirements will decrease substantially. This is shown in Appendix G calculations.

All six steps of sludge handling are shown in Figure 27. After converting labor and power to dollars per year and amortizing the capital costs and capital energy, a comparison can be made. Each step has one or more choices and dynamic programming is used to make the comparison.

Dynamic programming is a useful technique for making a sequence of interrelated decisions. In an N stage process such as shown in Figure 27, the best choice if sound in the N^{th} stage corresponding to all possible decisions that could be made in the $(N-1)^{th}$ stage. Now the two final stages are reduced into a single stage which all the possibilities and costs are known. Now proceed to examine the $(N-1)^{th}$ stage regarding the possible decisions in the $(N-2)^{th}$ stage. Following the same procedure all the stages down to the first stage can be examined. The restrictions or limitations for the six steps of sludge handling are given in Table 28.

TABLE 28

PROCESS LIMITATIONS

ITEM		RULE
FERT	must be preceeded by	Heat Treatment
LAG	must be preceeded by	Stabilization
LNF	must be preceeded by	Dewatering
INC	must be preceeded by	Dewatering
WO	must be preceeded by	Thickening
DB	must be preceeded by	Stabilization
VF, CT, PF	must be preceeded by	Conditioning
CC, HT, AND, AD	must be preceeded by	Thickening

The following example shows how this decision process works in the sludge handling flow scheme. The annual dollar values are used for comparison and are not exact costs for each process but are relative to one another.

For a flow of 1.0 MGD under Case 1 the annual cost of each process is given in Figure 28. Starting with the final disposal step or Step 6 the lowest dollar value is chosen with respect to the processes in Step 5. There are six choices available in Step 6.

The six choices in Step 6 have twenty-two possible combinations with Step 5. The three processes in Step 5 each have a cost in conjunction with Step 6. Table 29 shows the processes of Step 5 with the combinations of Step 6. The best combinations with regard to the three processes in Step 5 are incineration with landfill at an annual cost of $ 74,073 or $ 70,405, wet oxidation with lagooning at $ 60,241 per year and null with lagooning at $ 4,555 per year. This shows that landfill is best with incineration, lagooning is best with wet oxidation or null and fertilizer is never best. Now Steps 5 and 6 are combined as one solution step.

Following the same procedure Step 4 is examined in conjunction with the costs and limitations of the combinations of Steps 5 and 6. There are five possible processes of Step 4 and fifteen possible combinations with Steps 5 and 6. The best combinations with each dewatering process are drying beds with null and lagooning at $ 27,155, vacuum filter with null and lagooning at $ 28,224, centrifugation with null and lagooning at $ 58,241, pressure filtration with null and lagooning at $ 38,634 and null with null and lagooning at $ 4,555 per year. This shows that null of Step 5 and lagooning of Step 6 are best when used with drying beds, vacuum filters, centrifuges, pressure filters and null in the dewatering step. Incineration with landfill and wet oxidation with lagooning are never best when used with dewatering. The sludge handling has now been reduced to four steps as Steps 4, 5 and 6 are incorporated into one step.

The three processes of Step 3 can be examined with regard to the five choices made in Step 4. This makes fifteen possible process combinations. The best processes to be used with chemical conditioning are drying beds, null and lagooning at $39,989 per year. Heat

	GT	DAF	
	$9,191	$6,249*	STEP 1

	AND	AD	NULL
GT	$25,567	$12,299	$0
DAF	$25,567	$12,299*	$0

STEP 2

	CC	HT	NULL
AND	$12,834	N/A	$0
AD	$12,834	N/A	$0*
NULL	$12,834	$27,738	$0

STEP 3

	DB	VF	CT	PF	NULL
CC	$22,600	$33,669	$53,686	$34,079	N/A
HT	$22,600	$33,669	$53,686	$34,079	$0
NULL	N/A	N/A	N/A	N/A	$0*

STEP 4

	INC	WO	NULL
DB	N/A	N/A	$0
VF	$74,073	N/A	$0
CT	$74,073	N/A	$0
PF	$74,405	N/A	$0
NULL	N/A	$58,140	$0*

STEP 5

	FERT	LAG	LNF
INC	N/A	$2,101	$0
WO	N/A	$2,101	N/A
NULL	$46,923	$4,555*	$25,724

STEP 6

EXAMPLE PROCESS FLOWSHEET

FIGURE 28

TABLE 29

STEP 6 COMBINATIONS

Choice	Cost ($)	Combination	Total Annual Cost
LNF	0	INC W/ VF at $ 74073	74,073
LNF	0	INC W/ CT at $ 74073	74,073
LNF	0	INC W/ PF at $ 70405	70,405
LAG	2,101	INC W/ VF at $ 74073	76,174
LAG	2,101	INC W/ CT at $ 74073	76,174
LAG	2,101	INC W/ PF at $ 70405	72,506
LAG	2,101	WO W/ NULL at $ 58140	60,241
LAG	4,555	NULL W/ DB at $ 0	4,555
LAG	4,555	NULL W/ VF at $ 0	4,555
LAG	4,555	NULL W/ CT at $ 0	4,555
LAG	4,555	NULL W/ PF at $ 0	4,555
LAG	4,555	NULL W/ NULL at $ 0	4,555
FERT	46,923	NULL W/ DB at $ 0	46,923
FERT	46,923	NULL W/ VF at $ 0	46,923
FERT	46,923	NULL W/ CT at $ 0	46,923
FERT	46,923	NULL W/ PF at $ 0	46,923
FERT	46,923	NULL W/ NULL at $ 0	46,923
LNF	25,724	NULL W/ DB at $ 0	25,724
LNF	25,724	NULL W/ VF at $ 0	25,724
LNF	25,724	NULL W/ CT at $ 0	25,724
LNF	25,724	NULL W/ PF at $ 0	25,724
LNF	25,724	NULL W/ NULL at $ 0	25,724

treatment has no best combinations due to process limitations given in Table 28. The null of this Step is best with null, null and lagooning at an annual cost of $4,555. Now the sludge handling scheme consists of three steps since Steps 3, 4, 5 and 6 comprise one step.

Now Step 2 can be examined with regard to the combinations already determined. With the three processes of Step 2 there are six combinations available. Following the rules given the best combination to be used with anaerobic digestion is null, null, null and lagooning at a cost of $30,122 per year. Aerobic digestion works best with null, null, null and lagooning at an annual cost of $16,854.

The final choice to make is in Step 1 examined with the two schemes given from the combination of Steps 2, 3, 4, 5 and 6. There are two processes in Step 2 so there are four available combinations to choose from. The six steps have reduced down to one choice between four possible treatment schemes. They are gravity thickening, anaerobic digestion, null, null, null and lagooning at $39,313 per year; gravity thickening, aerobic digestion, null, null, null and lagooning at $26,045 per year; dissolved-air flotation, anaerobic digestion, null, null, null and lagooning at $36,371 per year; and dissolved-air flotation, aerobic digestion, null, null, null and lagooning at $23,103 per year.

The final sludge treatment choice is made with regard to the lowest dollar value and consists of gravity thickeners for thickening, aerobic digestion for stabilization, no conditioning, no dewatering, no reduction and lagooning for final disposal. It can be seen that even though the final disposal stop is not the cheapest the overall treatment scheme has the lowest cost.

The total treatment cost is about $23,103 per year. This is shown in Figure 28 where the chosen values are marked with an asterisk. The choice made for a flow at 1.0 MGD given above is the best choice possible when considering capital costs, and operating power and labor.

Following the procedure used in the example, the three design flows were analyzed according to three cases:

1. Economic optimum - 1975 and future
2. Energy affluent present with energy poor future
3. Energy optimum - 1975 and future

Figures 29 through 37 show the flow sheets and the costs of each individual process. The values are the ones used for the comparison.

For a plant flow of 1.0 MGD the sludge treatment scheme that would be best according to capital costs, operating power and operating labor consists of dissolved-air flotation, aerobic digestion and lagooning. The annual costs of this treatment scheme is about $ 23,103 (see Figure 29). This is a commonly used treatment scheme. This treatment scheme is the best choice when costs and energy inflate at the same rate and can be used for future planning.

If, at some time in the future, energy becomes scarce and the costs of power increase faster than inflation, then the treatment scheme that costs less and also uses the least amount of energy would be the best. Under Case 2 the annual costs are based only on the operating energy and capital costs. The treatment scheme with the lowest dollar value would be the best choice.

For the same plant flow of 1.0 MGD the best choice under Case 2 is lagooning, with its low power requirements, aerobic digestion and dissolved-air flotation (see Figure 30). This treatment scheme provides the best treatment and keeps the power consumption down. It is the same scheme chosen for the economic optimum (Case 1). The total cost is lower than Case 1 due to neglecting operating labor. Since the same treatment scheme is obtained for both Case 1 and Case 2, this shows that the processes are not labor sensitive.

The cost of capital energy is usually included in the capital cost of a product. If energy prices increase faster than inflation then products with a high capital energy component will have to increase in price accordingly. Under Case 3 the best treatment scheme chosen would be the one with the lowest capital and operating energy.

At a plant flow of 1.0 MGD the best treatment scheme was found to be lagooning with anaerobic digestion and gravity thickeners (see figure 31). This scheme is different from those chosen in Case 1 and Case 2. This shows that under expensive energy conditions anaerobic

	GT	DAF	
	$9,191	$6,249	STEP 1

	AND	AD	NULL
GT	$25,567	$12,299	$0
DAF	$25,567	$12,299	$0

STEP 2

	CC	HT	NULL
AND	$12,834	N/A	$0
AD	$12,834	N/A	$0
NULL	$12,834	$27,738	$0

STEP 3

	DB	VF	CT	PF	NULL
CC	$22,600	$22,600	$53,686	$34,079	N/A
HT	$22,600	$33,669	$53,686	$34,079	$0
NULL	N/A	N/A	N/A	N/A	$0

STEP 4

	INC	WO	NULL
DB	N/A	N/A	$0
VF	$74,073	N/A	$0
CT	$74,073	N/A	$0
PF	$70,405	N/A	$0
NULL	N/A	$58,140	$0

STEP 5

	FERT	LAG	LNF
INC	N/A	$2,101	$0
WO	N/A	$2,101	N/A
NULL	$46,923	$4,555	$25,724

STEP 6

FLOW 1.0 MGD-- CASE 1

FIGURE 29

GT	DAF	
$7,629	$3,835	STEP 1

	AND	AD	NULL	
GT	$23,969	$11,617	$0	STEP 2
DAF	$23,969	$11,617	$0	

	CC	HT	NULL	
AND	$5,450	N/A	$0	
AD	$5,450	N/A	$0	STEP 3
NULL	$5,450	$24,046	$0	

	DB	VF	CT	PF	NULL	
CC	$10,200	$22,069	$43,986	$19,279	N/A	STEP 4
HT	$10,200	$22,069	$43,986	$19,279	$0	
NULL	N/A	N/A	N/A	N/A	$0	

	INC	WO	NULL	
DB	N/A	N/A	$0	
VF	$60,583	N/A	$0	
CT	$60,583	N/A	$0	STEP 5
PF	$56,915	N/A	$0	
NULL	N/A		$0	

	FERT	LAG	LNF	
INC	N/A	$1,426	$0	
WO	N/A	$1,426	N/A	STEP 6
NULL	$26,191	$3,738	$10,956	

FLOW 1.0 MGD-- CASE 2

FIGURE 30

STEP 1

GT	DAF
$171	$1,837

STEP 2

	AND	AD	NULL
GT	$2,021	$2,603	$0
DAE	$2,021	$2,603	$0

STEP 3

	CC	HT	NULL
AND	$56	N/A	$0
AD	$56	N/A	$0
NULL	$56	$3,380	$0

STEP 4

	DB	VF	CT	PF	NULL
CC	$1,255	$730	$1,063	$750	N/A
HT	$1,255	$730	$1,063	$750	$0
NULL	N/A	N/A	N/A	N/A	$0

STEP 5

	INC	WO	NULL
DB	N/A	N/A	$0
VF	$7,141	N/A	$0
CT	$7,141	N/A	$0
PF	$3,473	N/A	$0
NULL	N/A	$6,720	$0

STEP 6

	FERT	LAG	LNF
INC	N/A	$0	$0
WO	N/A	$0	N/A
NULL	$24,111	$0	$6,526

FLOW 1.0 MGD--CASE 3

FIGURE 31

digestion is better than aerobic digestion and gravity thickening is better than dissolved-air flotation thickening.

As the flow increases the treatment schemes obtained under the three cases change. Going from a flow of 1.0 MGD to 10.0 MGD at Case 1, the economic optimum, the scheme changes from lagooning, aerobic digestion and dissolved-air flotation to lagooning, anaerobic digestion and gravity thickening. The annual cost of this treatment is about $ 110,896. The treatment scheme changes because the aerobic digestion and dissolved-air flotation processes use too much energy at this size plant (see Figure 32).

Increasing the flow to 10.0 MGD under Case 2 causes the same changes it did under Case 1. The treatment scheme consists of lagooning, anaerobic digestion and gravity thickening (see Figure 33). This is the same scheme chosen as the economic optimum (Case 1). Labor is still not a dominant factor in the decision.

At 10.0 MGD for Case 3 the treatment does not change from the choices made for Case 1 and Case 2 (see Figure 34). The lagoons with anaerobic digestion and gravity thickeners are still the best choice. This treatment is the same chosen for the 1.0 MGD plant.

Increasing the plant flow to 100.0 MGD does not alter any choices made at the 10.0 MGD flow for all three cases. Lagooning, anaerobic digestion and gravity thickening is the best choice when considering costs, labor and energy (Case 1); costs and energy (Case 2); and energy (Case 3) (see figures 35, 36, and 37). The estimated annual cost for treatment at this scheme under Case 1 is $ 758,472.

At Case 2, however, lagooning with incineration, pressure filtration, chemical conditioning and gravity thickening was only about $ 100,000 per year more than the treatment chosen. If maximum maintenance and operational care was exercised the two treatment schemes might be comparable. Since incineration reduces the lagoon area by 60%, the choice of treatment could be altered in this case if the price and availability of land were more significant factors.

As a final disposal step lagooning is the best choice to keep costs and energy requirements low for all three design flows. Table 30 shows the treatment choices of all three cases for all three design

STEP 1

GT	DAF
$25,521	$47,280

STEP 2

	AND	AD	NULL
GT	$69,508	$73,344	$0
DAF	$69,508	$73,344	$0

STEP 3

	CC	HT	NULL
AND	$27,243	N/A	$0
AD	$27,243	N/A	$0
NULL	$27,243	N/A	$0

STEP 4

	DB	VF	CT	PF	NULL
CC	$213,926	$94,315	$120,563	$80,989	N/A
HT	$213,926	$60,169	$120,563	$80,989	$0
NULL	N/A	N/A	N/A	N/A	$0

STEP 5

	INC	WO	NULL
DB	N/A	N/A	$0
VF	$146,457	N/A	$0
CT	$146,457	N/A	$0
PF	$140,161	N/A	$0
NULL	N/A	$219,441	$0

STEP 6

	FERT	LAG	LNF
INC	N/A	$6,229	$25,724
WO	N/A	$6,229	N/A
NULL	$469,247	$15,867	$94,133

FLOW 10.0 MGD -- CASE 1

FIGURE 32

GT	DAF	
$19,983	$39,470	STEP 1

STEP 2

	AND	AD	NULL
GT	$61,520	$69,936	$0
DAF	$61,520	$69,936	$0

STEP 3

	CC	HT	NULL
AND	$8,963	N/A	$0
AD	$8,963	N/A	$0
NULL	$8,963	$76,409	$0

STEP 4

	DB	VF	CT	PF	NULL
CC	$89,626	$54,215	$90,763	$44,089	N/A
HT	$89,626	$20,069	$90,763	$44,089	$0
NULL	N/A	N/A	N/A	N/A	$0

STEP 5

	INC	WO	NULL
DB	N/A	N/A	$0
VF	$108,117	N/A	$0
CT	$108,117	N/A	$0
PF	$101,821	N/A	$0
NULL	N/A	$210,211	$0

STEP 6

	FERT	LAG	LNF
INC	N/A	$5,093	$10,956
WO	N/A	$5,093	N/A
NULL	$261,927	$14,198	$57,213

FLOW 10.0 MGD -- CASE 2

FIGURE 33

GT	DAF	
$429	$13,359	STEP 1

	AND	AD	NULL	
GT	$9,827	$29,749	$0	STEP 2
DAF	$9,827	$29,749	$0	

	CC	HT	NULL	
AND	$1,166	N/A	$0	
AD	$1,166	N/A	$0	STEP 3
NULL	$1,166	$34,083	$0	

	DB	VF	CT	PF	NULL	
CC	$5,539	$6,272	$5,021	$6,912	N/A	
HT	$5,539	$730	$5,021	$6,912	$0	STEP 4
NULL	N/A	N/A	N/A	N/A	$0	

	INC	WO	NULL	
DB	N/A	N/A	$0	
VF	$15,711	N/A	$0	
CT	$15,711	N/A	$0	STEP 5
PF	$9,415	N/A	$0	
NULL	N/A	$67,491	$0	

	FERT	LAG	LNF	
INC	N/A	$0	$6,526	
WO	N/A	$0	N/A	STEP 6
NULL	$241,132	$0	$37,976	

FLOW 10.0 MGD -- CASE 3

FIGURE 34

	GT	DAF	
	$111,663	$399,755	STEP 1

	AND	AD	NULL
GT	$569,617	$704,449	$0
DAF	$569,617	$704,449	$0

STEP 2

	CC	HT	NULL
AND	$142,369	N/A	$0
AD	$142,369	N/A	$0
NULL	$142,369	$612,399	$0

STEP 3

	DB	VF	CT	PF	NULL
CC	$2,410,484	$577,828	$519,480	$403,534	N/A
HT	$2,410,484	$310,415	$519,480	$403,534	$0
NULL	N/A	N/A	N/A	N/A	$0

STEP 4

	INC	WO	NULL
DB	N/A	N/A	$0
VF	$624,233	N/A	$0
CT	$624,233	N/A	$0
PF	$588,230	N/A	$0
NULL	N/A	$1,352,516	$0

STEP 5

	FERT	LAG	LNF
INC	N/A	$26,332	$75,661
WO	N/A	$26,332	N/A
NULL	$4,692,473	$77,192	$306,592

STEP 6

FLOW 100.0 MGD -- CASE 1

FIGURE 35

	GT	DAF	
	$86,103	$364,255	STEP 1

	AND	AD	NULL
GT	$529,147	$687,267	$0
DAF	$529,147	$687,267	$0

STEP 2

	CC	HT	NULL
AND	$111,356	N/A	$0
AD	$111,356	N/A	$0
NULL	$111,356	$596,850	$0

STEP 3

	DB	VF	CT	PF	NULL
CC	$1,167,984	$325,728	$306,480	$217,434	N/A
HT	$1,167,984	$58,315	$306,480	$217,434	$0
NULL	N/A	N/A	N/A	N/A	$0

STEP 4

	INC	WO	NULL
DB	N/A	N/A	$0
VF	$347,333	N/A	$0
CT	$347,333	N/A	$0
PF	$311,330	N/A	$0
NULL	N/A	$1,336,967	$0

STEP 5

	FERT	LAG	LNF
INC	N/A	$22,427	$38,741
WO	N/A	$22,427	N/A
NULL	$2,619,273	$67,252	$244,566

STEP 6

FLOW 100.0 MGD -- CASE 2

FIGURE 36

STEP 1

GT	DAF
$1,879	$102,996

STEP 2

	AND	AD	NULL
GT	$61,202	$352,320	$0
DAF	$61,202	$352,320	$0

STEP 3

	CC	HT	NULL
AND	$11,889	N/A	$0
AD	$11,889	N/A	$0
NULL	$11,889	$337,680	$0

STEP 4

	DB	VF	CT	PF	NULL
CC	$19,240	$59,469	$49,195	$68,383	N/A
HT	$19,240	$6,272	$49,195	$68,383	$0
NULL	N/A	N/A	N/A	N/A	$0

STEP 5

	INC	WO	NULL
DB	N/A	N/A	$0
VF	$66,852	N/A	$0
CT	$66,852	N/A	$0
PF	$30,849	N/A	$0
NULL	N/A	$671,901	$0

STEP 6

	FERT	LAG	LNF
INC	N/A	$0	$18,989
WO	N/A	$0	N/A
NULL	$2,411,318	$0	$158,193

FLOW 100.0 MGD -- CASE 3

FIGURE 37

TABLE 30

FINAL TREATMENT SCHEMES

	Case 1			Case 2			Case 3		
Steps	1.0	10.0	100.0	1.0	10.0	100.0	1.0	10.0	100.0
1	DAF	GT	GT	DAF	GT	GT	GT	GT	GT
2	AD	AND	AND	AD	AND	AND	AND	AND	AND
3	---	---	---	---	---	---	---	---	---
4	---	---	---	---	---	---	---	---	---
5	---	---	---	---	---	---	---	---	---
6	LAG	LAG	LAG	LAG	LAG	LAG	LAG	LAG	LAG
Total Costs	$ 23103	$ 110896	$ 758742	$ 19190	$ 95701	$ 692502	$ 2192	$ 10256	$ 63081

flows with their respective total costs. As seen in Table 30 treatment steps three, four and five can be omitted thus reducing cost and energy consumption.

CONCLUSIONS

The best treatment for sludge varies with flow and energy requirements. Considering treatment costs only the best treatment scheme consists of lagooning, aerobic digestion and dissolved-air flotation for the 1.0 MGD plant but switches to lagooning, anaerobic digestion and gravity thickening for the 10.0 MGD and the 100.0 MGD plants. The choice of treatment here is the economic optimum for 1975 and also for any time in the future assuming inflation affects all processes equally.

Removing the labor costs and comparing the processes only capital costs and operating power does not change any of the treatment choices. Lagooning with digestion and thickening stages presents the best treatment if operating power consumption becomes a major factor. This choice of treatment will use the least power when power prices increase dramatically.

Looking at the processes with regard to only the capital and operating energy, the best treatment scheme is lagooning with anaerobic digestion and gravity thickening for all three design flows. This choice of treatment results in the lowest energy consumption and could be used for future planning. Since the treatment scheme has the lowest energy consumption, when the price of energy increases faster than inflation this specific scheme will have the smallest net increase in cost, compared to other possible choices.

In all nine treatment schemes examined there are no reduction, dewatering or conditioning steps involved. Sludge can be treated effectively without these steps. Since there is an end product to be disposed of with any type of treatment, then stabilization and thickening are all that is needed with the final disposal. No excess treatment should be used in order to keep the costs and energy requirements to a minimum.

APPENDICES

APPENDIX A

SLUDGE AND ENERGY CALCULATIONS

SLUDGE CALCULATIONS

Assumptions:

Influent B.O.D. = 200 mg/l = S_o

$(200 \text{ mg/l})(8.34) = 1668 \text{ lb/day}/10^6$ gallons

Influent Suspended Solids = 200 mg/l = X

$(200 \text{ mg/l})(8.34) = 1668 \text{ lb/day}/10^6$ gallons

Raw Primary Sludge:

Efficiency of primary clarifier = 60% X_o; 30% S_o

$(1668 \text{ lb/day})(60\%) = 1000.8 \text{ lb/day}/10^6$ gallons

At 5% solids and specific gravity of 1.03 the volume of sludge per 10^6 gallons is:

$$\frac{(1000.8 \text{ lb/day})}{(1.03)(0.05)(8.34)} = 2{,}330 \text{ gallons/day}$$

Waste Activated Sludge:

B.O.D. removed = (ΔS) = influent BOD - effluent BOD

$\Delta S = 70\% (200 \text{ mg/l}) - 10\%(70\%)(200 \text{ mg/l})$

$= 126 \text{ mg/l} = 1052 \text{ lb/day}/10^6$ gallons

Net solids production (ΔX) = ΔS (yield)

$\Delta X = 1052 \text{ lb/day } (0.5) = 526 \text{ lb/day}$

Total waste activated sludge = $(1-K) X_o - X_f + (X)$

K = fraction of solids removed in primary tanks

X_f = effluent suspended solids

$(1-0.6)(1668 \text{ lb/day}) - (15 \text{ mg/l})(8.34) + 526 \text{ lb/day}$

1068 lb/day = waste activated sludge

At 0.75% solids and a specific gravity of 1.03 the volume of sludge per 10^6 gallons is:

$$\frac{(1068 \text{ lb/day})}{(1.03)\ (0.0075)\ (8.34)} = 16,578 \text{ gallons/day}$$

Total Mixed Sludge:

$$\frac{(1000.8 \text{ lb/day} + 1068 \text{ lb/day})}{(1.03)\ (62.4) \text{ lb/cu. ft.})\ (1.27\%)} \quad 2533.5 \text{ ft}^3\text{/day}$$

where 1.03 is the specific gravity and 1.27% is the solids concentrations of the mixed sludge from the following mass balance:

$$\frac{(5\%)\ (2330 \text{ gal}) + (0.75\%)\ (16,578 \text{ gal})}{(18,908 \text{ gal})} = 1.27\%$$

CAPITAL ENERGY DATA

Steel:[30]

From manufacturer's information the energy used for one ton of finished steel is about 36 million B.T.U.'s. The breakdown is about 71% coal, 18% natural gas, 7% fuel oil and 4% electricity.

Concrete:[31-32]

Using a maximum size aggregate of 1.5 inches the make up of concrete is:

Aggregate = 20 ft^3/yd^3
Air = 1 ft^3/yd^3
Cement = 2.5 ft^3/yd^3
Water = 3.5 ft^3/yd^3 with a water cement ratio of 0.54 by volume. For every cubic yard of concrete there is about 2.5 sacks of cement. At an energy value of 175,000 BTU's per sack, a cubic yard of concrete takes about 437,500 BTU's to produce.

APPENDIX B

THICKENING CALCULATIONS

GRAVITY THICKENER[25]

Assumptions:

$$A_t = \frac{Q_w (M_{tw}) (8.34)}{G_L}$$

where G_L = 6 lb/ft^2/day for a thickened sludge of 6%; Q_w = sludge flow, MGD; M_{tw} = sludge concentration, mg/l; and A_t = area of tank, ft^2.

Tanks are to be 15 feet deep.[3]

Size:

Plant Size (MGD)	Q_w	Area (ft^2)	Diameter (ft)
1	0.019	336.3	20.7
10	0.189	3362.7	65.4
100	1.891	33627.9	206.9

Cost:

Diameter (ft)	Cost* (1972 $)	Cost (1975 $)	Adj. Cost** (1975 $)
20.7	57,000	68,733	73,800
65.4	150,000	180,877	194,000
206.9	650,000	783,800	841,000

*from Figure 1

** based on E.P.A. number of 1.073 for Region V

Costs include purchased cost of thickener, erection, site preparation, pumps, piping, concrete, steel, instrumentation, electrical, paint and indirect costs.[4]

Capital Energy Requirements:

Weight of raking mechanisms (steel):

Dia. (ft)	Weight* (lb)	(tons)	Energy** (BTU x 10^6)
20.7	2605	1.30	46.8
65.4	8500	4.25	153.0
206.9	56100	28.05	1010.0

*from reference 36

** based on 36 x 10^6 BTU's/ton

Wall volumes (concrete)

Dia. (ft)	Depth (ft)	Volume of Wall* (ft^3)	(yd^3)	Energy** (BTUx10^6)
20.7	15	500	18.5	8.2
65.4	15	1553	57.5	25.2
206.9	15	4887	181.0	79.2

*based on 12 inch thick walls

** based on 437,500 BTU's/yd^3

Floor volumes (concrete):

Area (ft^2)	Volume of Floor* (ft^3)	(yd^3)	Energy** (BTUx10^6)
336.3	336.3	12.5	5.6
3362.7	3362.7	124.5	54.5
33627.9	33627.9	1245.5	544.9

*based on 12 in. floor slabs

** based on 437,500 BTU's/yd^3

Total capital energy:

the total capital energy is the sum of the steel and concrete in B.T.U.'s.

Plant size (MGD)	Capital energy (million BTU's)
1	66
10	230
100	1600

Operating Power and Labor:

Plant size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	10.2	220
10	20.4	780
100	40.8	3600

*from Table 1

** from Figure 3

DISSOLVED-AIR FLOTATION[5]

Assumptions:

Solids loading = 2 lb/hr/ft^2

Solids recovery = 50 to 80%

Design solids = 4%

Maximum hydraulic loading = 0.8 gpm/ft^2

Best clarification time = 30 minutes

$$\text{Area, ft}^2 = \frac{(2068\ \text{lb/day}/10^6\ \text{gal})\ (7\ \text{day/week})}{(2\ \text{lb/hr/ft}^2)\ (\text{hours worked/week})}$$

Size:

Plant Size (MGD)	Operation (hrs/week)	Tank area (ft^2)
1	40	181
10	100	724
100	168	4308

sizes would be half those stated if only waste activated sludge was thickened.

Cost:

Area (ft^2)	Capacity* (ft^3)	Cost** (1972$)	Adj. Cost ‡ (1975 $)
181	56	15,000	22,600
724	560	170,000	256,750
4308	5600	1,700,000	2,567,500

*based on 56 ft^3 of sludge/30 minutes

** from Figure 4

‡ based on EPA number 1.139 for Region V

Costs include installed flotation machine, motor and drive, piping, concrete, steel, instrumentation and indirect costs.[4]

Capital Energy Requirements:

- if steel tanks are used:

Area (ft^2)	Steel* Tanks	Weight* (lb-ea)	(ton)	Energy** (BTU's)
181	1 at 200 ft^2	18850	9.43	339.5×10^6
724	3 at 250 ft^2	22150	33.23	1196.3×10^6
4308	10 at 450 ft^2	32600	163.0	5868.0×10^6

*from reference 36

** based on 36×10^6 BTU's/ton

- if concrete tanks are used:

Tank Length (ft)	Tank Width (ft)	Tank Area (ft^2)	No. of Tanks
--	--	--	--
10	40	400	2
10	45	450	10

Volume of Concrete Walls* (ft^3)	Floors** (ft^3)	Total (yd^3)	Energy‡ (BTU's x 10^6)
---	---	---	N/A
2364	676	112.6	49.3
12870	3750	615.6	269.3

*based on 12 in. support walls and 9 in. non-support walls and a depth of 10.5 feet; five foot wet wall added

** based on a 9 in. slab thickness; five foot wet well added.

‡ based on 437,500 BTU's/yd^3

Operating Power and Labor

Plant size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	140.0	340
10	1216.0	1100
100	9384.0	5000

*from Table 3 - doubled due to twice the volume of sludge

** from Figure 5

ANNUAL COSTS - STEP 1

Power:

Plant Size (MGD)	Power (kwh/day)		Cost ($/yr)*	
	GT	DAF	GT	DAF
1	10.2	140	112	1533
10	20.4	1216	223	13315
100	40.8	9384	447	102755

*based on $0.03/kwh

Labor:

Plant Size (MGD)	Labor (hrs/yr)		Cost ($/yr)*	
	GT	DAF	GT	DAF
1	220	340	1562	2414
10	780	1100	5368	7810
100	3600	5000	25560	35500

*based on $7.10 per hour.

Capital Costs:

Plant Size (MGD)	Cost ($)		Cost ($/yr)*	
	GT	DAF	GT	DAF
1	73800	22600	7517	2302
10	194000	256800	19760	26155
100	841000	2567500	85656	261500

*amortization at 8% over 20 years.

Capital Energy:

Plant Size (MGD)	Capital Energy ($BTU \times 10^6$) GT conc.	DAF steel	DAF conc.	Cost* ($/year) GT conc.	DAF steel	DAF conc.
1	66	340	N/A	59	304	N/A
10	230	1196	49	206	1071	44
100	1600	5868	269	1432	5253	241

*based on $0.03/kwh and 3413 BTU/KWH and then amortized at 8% over 20 years.

ANNUAL COST OF CASES - STEP 1

Case 1 (Power, labor and capital costs)

Plant Size (MGD)	GT ($/yr)	DAF ($/yr)
1	9191	6249
10	25521	47280
100	111663	399755

Case 2 (Capital costs and power)

Plant Size (MGD)	GT ($/yr)	DAF ($/yr)
1	7629	3835
10	19983	39470
100	86103	364255

Case 3 (Capital energy and power)

Plant Size (MGD)	GT ($/yr)	DAF-steel ($/yr)	DAF-conc. ($/yr)
1	171	1837	N/A
10	429	14386	13359
100	1879	108008	102996

APPENDIX C

STABILIZATION CALCULATIONS

ANAEROBIC DIGESTION

Assumptions:

Loading = 30 to 100 lb volatile solids/1000 ft^3/day

Detention time = 30 days

Temperature = 85 to 95^{o}F

Mean All Residence Time = 10 days

Sludge flow rate = $\dfrac{2068 \text{ lb/day}}{(62.4 \frac{\text{lb}}{\text{ft}^3})(1.03)(0.05)} = 644 \dfrac{\text{ft}^3}{\text{day}}$

where 1.03 = specific gravity

0.05 = percent solids of influent

Volume of digester = Sludge flow rate x detention time

= (644 ft^3/day) (30 days)

= 19,320 ft^3

Size:

Plant Size (MGD)	Tank Vol. (ft^3)	No. of Tanks	Tank Dia (ft)	Water Depth(ft)	Total* Depth(ft)
1	19,320	1	35	20.0	22.0
10	193,200	3	55	27.1	29.6
100	1,932,000	6	110	33.9	36.4

*2.0 feet freeboard for tanks less than 50 feet in diameter and 2.5 feet for tanks with diameters greater than 50 feet.

Tanks are circular and are seldom less than 20' or more than 115 feet in diameter; water depth of not less than 25 feet at the center is recommended.

Cost:

Plant Size (MGD)	Dig Vol (ft^3)	Capital* Cost (1972)	Capital Cost (1975)
1	19,320	160,000	222,000
10	193,200	400,000	555,000
100	1,932,000	3,600,000	4,990,000

*from Fig. 9

Costs will double if a thickening digester is installed.

Capital Energy Requirements

Covers (steel)[34]

Plant Size (MGD)	Cover Area (ft^2)	Wt of* Covers (tons)	Capital Energy** (BTU's x 10^6)
1	962 ea	16.8 ea = 16.8	605
10	2376 ea	41.6 ea = 124.8	4493
100	9503 ea	166.3 ea = 997.8	35921

*based on 35 lb/ft^2 of cover

** based on 36 x 10^6 BTU/ Ton

Heaters (Steel)[34]

1. to raise temperature of incoming sludge

$$BTU/hr = \frac{(2068\ lb/day)\ (100)\ (95^o - 68^o)}{(24\ hrs/day)\ (5\ \%)}$$

$= 46,530$ per 10^6 gallons

2. to offset heating losses

(assuming a well insulated covers and well insulated side walls no gas recirculation)

2600 BTU/HR/1000 ft^3 x 0.9 = 2340

where 0.9 is the Michigan geographic correction factor.

Plant Size (MGD)	Dig Vol (ft^3)	Heat for Temp (BTU/hr)	Heat for Losses (BTU/hr)	Total Heat (BTU/hr)
1	19,320	46,530	45,208	91,738
10	193,200	465,300	452,088	917,388
100	1,932,000	4,653,000	4,520,880	9,173,880

Heater* Size (BTU/hr)	Heater* Weight(lbs)
140,000	5,600
1,000,000	20,400
3 at 3,500,000	104,000

*from reference 34

Tanks (Concrete):

Tank Dia (ft)	No. of Tanks	Tank Depth (ft)	Wall* Vol ea. (ft^3)	Floor Vol ea. (ft^3)	Total Vol (yd^3)
35	1	22	1227	990	82
55	3	29.6	2580	2445	558
110	6	36.4	6318	9764	3574

*based on 12 inch thickness

** based on 12 inch thickness and 1 to 6 floor slope.

Total Capital Energy:

Plant Size (MGD)	Heaters* (BTU x 10^6)	Covers* (BTU x 10^6)	Tanks** (BTU x 10^6)	Total (BTU x 10^6)
1	100.8	605	35.9	741.7
10	367.2	4493	558	5418.2
100	5616	35921	3574	54111.0

*based on 36 x 10^6 BTU/Ton of steel

** based on 437,500 BTU's/yd^3 of concrete

Operating Power and Labor:

Plant Size (MGD)	Power (KWH/day)*	Labor (hr/yr)**
1	123.6	225
10	456.4	1125
100	1910.0	5700

*from Table 6, methane gas will provide extra heater fuel.

Methane Production:

1 ft^3 of methane (at 70°F and 1 atm) has a net heating value of 960 BTU. Digester gas, 65% methane, has a heating value of 600 BTU/ft^3 [63]

Quantity of methane gas can be calculated[63] from

$$C = 5.62\left(ef - 1.42\frac{dx}{df}\right) \text{ where } C = ft^3 \text{ of } CH_4/\text{day}$$

(See Appendix A)

e = efficiency of waste utilization

F = BOD_L added, lb/day

$\frac{dx}{df}$ = net growth rate

F = 2068 lb/day

$\frac{dx}{df}$ = 526 lb/day

e = 0.75 (average)[63]

$$C = 5.62\,[(0.75)(2068 \text{ lb/day}) - 1.42\,(526 \text{ lb/day})]$$

$$= 4519 \text{ ft}^3 / 10^6 \text{ gallons treated.}$$

Plant Size (MGD)	CH_4 (ft^3/day)	Heat Value* (BTU/day)	Heat Needed (BTU/day)
1	4519	4.4×10^6	2.2×10^6
10	45189	4.4×10^7	2.2×10^7
100	451892	4.4×10^8	2.2×10^8

*based on 960 BTU/ft^3 of CH_4

** due to heat losses and heat requirements

Since gas produced is more than gas needed there will be no extra fuel needed.

AEROBIC DIGESTION:

Assumption:

Current practice is to provide 15 days of detention time for waste activated sludge. More time required if primary sludge is involved. Use 20 days.[30]

Hydraulic detention time = 18 to 22 days at 20°C.

Solids loading = 0.1 to 0.2 lb vss/ft^3/day

O_2 requirements = 1.6 to 1.9 lb BOD_5/lb destroyed

Energy requirements for mixing:

mechanical = 0.5 to 1.0 hp/1000 ft^3

air mixing = 20 to 30 SCFM/1000 ft^3

Solids = 644 ft^3/day (See Anaerobic digestion)

Volume of Digesters = (644 ft^3/day) (20 days) = 12880 ft^3

Air req'd = (25 SCFM/1000 ft^3) (12880 ft^3) = 322 SCFM

at 6.5 psi estimated BHP = 12.0

Size:

Plant Size (MGD)	Dig. Vol (ft^3)	No. of Tanks	Tank Dimensions Depth (ft)	Length (ft)	Width (ft)	Vol (ft)
1	12880	1	10.7	60	20'	12960
10	128800	4	12.5	130	20'	130000
100	1288000	20	15.0	172	25'	1290000

Plant	Air (SCFM)	No. Blowers	Est* (BHp)	Wt. (lbs)
1	322	1	13	400
10	3220	1	150	2580
100	32200	4	1784	25200

*based on 1.0 foot loss in diffusers, 30% loss in piping and an efficiency of 70%.[26]

Cost:

Plant Size (MGD)	Cost* (1972 $)	Cost (1975 $)
1	67,000	89,000
10	300,000	398,000
100	2,500,000	3,315,000

Capital Energy Requirements:

Tanks (Concrete):

Plant Size (MGD)	Dig. Vol (ft^3)	Walls* (ft^3)	Floor** (ft^3)	Total (yd^3)
1	12960	1830	1200	113
10	130000	10780	10400	785
100	1290000	71973	86000	5851

*based on support walls 12 inches thick, non support walls 9 in. thick and 1.5 feet freeboard

** based on 12 in. thick slab.

Capital Energy:

Plant Size (MGD)	Blower Wt. (tons)	Tank Vol (yd^3)	Capital Energy Steel* (BTU x 10^6)	Concrete** (BTU x 10^6)	Total (BTU x 10^6)
1	0.20	113	7.2	49.4	56.6
10	1.29	785	46.4	343.4	389.8
100	12.60	5851	453.6	2560.0	3013.6

*based on 36 x 10^6 BTU/ton of steel

** based on 437,500 BTU/yd^3 of concrete

Operating Power and Labor:

Plant Size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	232.7	96
10	2685.0	480
100	31928.0	2420

*based on estimated BHp of blowers and an operating efficiency of 70%

** from Figure 8

ANNUAL COSTS - STEP 2

Power:

Size (MGD)	Power (kwh/day) AND	AD	Costs ($ /yr)* AND	AD
1	124	233	1358	2552
10	456	2685	4993	29400
100	1910	31930	20915	349634

*based on $ 0.03/kwh

Labor:

Size (MGD)	Labor (hrs/yr) AND	AD	Costs ($ /yr)* AND	AD
1	225	96	1598	682
10	1125	480	7988	3408
100	5700	2420	40470	17182

*based on $ 7.10/hr

Capital Cost:

Size (MGD)	Costs ($) AND	AD	Costs ($ /yr)* AND	AD
1	222000	89000	22600	9065
10	555000	398000	56527	40536
100	4990000	3315000	508232	337633

*based on 8% over 20 years

Capital Energy:

Size (MGD)	Capital Energy (BTU) AND	AD	Cost* ($ /yr) AND	AD
1	7.4×10^8	5.7×10^7	663	51
10	5.4×10^9	3.9×10^8	4834	349
100	4.5×10^{10}	3.0×10^9	40287	2686

*based on $ 0.03/kwh and 3413 BTU/kwh and amortized at 8% over 20 years.

ANNUAL COST OF CASES - STEP 2

Case 1 (Power Labor, Capital Cost):

Size (MGD)	AND ($ /yr)	AD ($ /yr)
1	25567	12299
10	69508	73344
100	569617	704449

Case 2 (Capital Costs and Power):

Size (MGD)	AND ($/yr)	AD ($/yr)
1	23969	11617
10	61520	69936
100	529147	687267

Case 3 (Capital Energy and Power):

Size (MGD)	AND ($/yr)	AD ($/yr)
1	2021	2603
10	9827	29749
100	61202	352320

APPENDIX D

CONDITIONING CALCULATIONS

CHEMICAL CONDITIONING

Assumptions:

$FeCl_3$ dosage = 1.5 to 2.5 % for fresh solids
= 1.5 to 4.0 % for digested

Use 2.0 % for design. Equipment will be bigger if digested sludge is used.

Dewatering is the main step that uses chemical conditioning.

Solids = 5 % influent

Tanks must be lined with rubber.

Contact time = 30 minutes

If polyelectrolytes are used - feeders will be smaller

(2068 lb/day) (2.0 %) = 41.36 lb/day/10^6 gallons

Size:

Feeders:

Plant Size (MGD)	Sludge (lb/day)	Chemicals* (lb/day)	Chemicals (lb/min)
1	2068	41.4	0.03
10	20680	413.6	0.29
100	206800	4136.0	2.87

*based on 2 % feed.

Mixing Tanks:

Plant Size (MGD)	Vol of Sludge (gal/day)	Vol of Chemicals (gal/day)	Total Vol (gal/day)	Tank* Vol (gal)	Hp** Required per hr
1	18908	378	19286	401.8	0.5
10	189080	3782	192862	4017.9	6.0
100	1890800	37816	1928616	40179.2	40.0

*based on 30 min detention time.
** from reference 35 -- 0.25 hp for 250 gal tank.
0.50 hp for 500 gal tank.

Cost:

Plant Size (MGD)	Feed Rate (lb/min)	Feed Volume (gal)	Mixing* Tank Vol (gal)	Cost (1972$)** Feeder Cost	Mixing Tank
1	0.03	378	401.8	4500	30000
10	0.29	3782	4017.9	10000	52000
100	2.87	37816	40179.2	23000	170000

*based on 30 min detention time

** from references 4 and 35.

Cost include purchased cost of equipment, motors, handling and setting, concrete, steel, electrical, instrumentation, insulation, paint and indirect costs.[4]

Cost (1975$)	Chemical Cost* (1975 $/yr)
45800	755.6
79400	7548.2
256000	75482.0

*based on 5¢/lb dry basis (East Lansing Sewage T.P.)

Capital Energy Requirements:

Plant Size (MGD)	Mixing Tanks* Vol (gal)	Wt. (lbs)	No. of Tanks	Capital** energy (BTU x 10^6)
1	402	1600	1 at 500	28.8
10	4018	18000	12 at 350	324.0
100	40180	129600	81 at 500	2332.8

*from reference 35; stainless steel and includes feeder weight

** based on 36 x 10^6 BTU/ton of steel

Operating Power and Labor:

Plant Size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	2.7	1040
10	80.0	2600
100	895.0	4368

*based on Hp required for mixing in Hphr: 1 Hphr = 0.7457 kwhr) and a 80% efficiency

** based on 0.5 operators per shift (MAX)[4]

HEAT TREATMENT

Assumptions:

Pressure = 180 to 210 psig

Residence time = 0.5 hours

Temperature = 350^{o} to $390^{o}F$

Heat treatment is a wet oxidation process at lower pressures and temperatures. Therefore size, construction requirements and operating labor are the same. (See Appendix F).

Size: (Envirotech-Eimco):

Plant Size (MGD)	Reactor* Vol. (gal)	No. of Reactors	Vol. of Reactors
1	394	2	250 gal each
10	3939	1	4300 gal
100	39392	5	8000 gal each

*based on 30 minute detention time

Cost:

Plant Size (MGD)	Loading (lb/hr)	Cost* (1970 $)	Cost (1975 $)
1	86.2	130000	203300
10	861.7	270000	422300
100	8616.7	3 at 550000	2581000

*from Figure 24

Capital Energy Requirements:

(due to reactor and its respective heat exchanger)

Plant Size (MGD)	Reactor Vol. (gal)	Reactor* Wt. (lbs)	Heater Ex.* Wt. (lbs)	Total Wt. (tons)	Energy** ($BTU \times 10^6$)
1	500	2500	N/A	1.3	45
10	4300	16700	25800	21.3	765
100	40000	141400	99700	120.6	4339.8

*from manufacturing data

** based on 36×10^6 BTU/ton of steel

Operating Power and Labor:

Plant Size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	305	520
10	3050	1300
100	30500	2190

*from reference 30; power includes electricity and fuel. Assumed to be half the power needed for wet oxidation.

** based on 0.25 men per hour of operation.[4]

ANNUAL COSTS - STEP 3

Power:

Size	Power (kwh/day)		Cost ($ /yr)*	
(MGD)	CC	HT	CC	HT
1	2.7	305	30	3340
10	80	3050	876	33398
100	895	30500	9800	333975

*based on $ 0.03/kwh

Labor:

Size	Labor (hr/yr)		Cost ($ /hr)*	
(MGD)	CC	HT	CC	HT
1	1040	520	7384	3692
10	2600	1300	18460	9230
100	4368	2190	31013	15549

*based on $ 7.10/hr

Capital Cost:

Size	Cost ($)		Cost ($ /yr)*	
(MGD)	CC	HT	CC **	HT
1	45800	203300	5420	20706
10	79400	422300	8087	43011
100	256000	2581000	101556	262876

*based on 8% over 20 years.

** includes chemical cost.

Capital Energy:

Size (MGD)	Capital Energy (BTU x 10^6) CC	HT	Annual Cost* CC	HT
1	29	45	26	40
10	324	765	290	685
100	2333	4339	2089	3885

*based on $0.03/kwh and 2.93 x 10^{-4} kwh/BTU and amortized at 8% over 20 years.

ANNUAL COST OF CASES -STEP 3

Case 1 (Capital Cost, Power, Labor)

Size (MGD)	CC ($/ yr)	HT ($/yr)
1	12834	27738
10	27423	85639
100	142369	612399

Case 2 (Capital Cost and Power)

Size (MGD)	CC ($/yr)	HT ($/yr)
1	5450	24046
10	8963	76409
100	111356	596850

Case 3 (Capital Energy and Power)

Size (MGD)	CC ($/yr)	HT ($/yr)
1	56	3380
10	1166	34083
100	11889	337860

APPENDIX E

DEWATERING

DRYING BEDS

Assumptions:

For mixed primary and waste activated digested sludge assume a loading of 15 $lb/ft^2/year$ (Open Beds - Northern Climate)

30% solids concentration assumed

2068 lb sludge for each 10^6 gallons treated

(2068 lb/day) (365 days/year) = 754,820 lb/year

$$\frac{(754,820 \text{ lb/year})}{(15 \text{ lb/ft}^2\text{/year})} = 50,321 \text{ ft}^2 = 1.16 \text{ acres}$$

Size:

Plant Size (MGD)	Solids (lb/yr)	Bed Area (ft^2)	Acres
1	754820	50321	1.16
10	7548200	503210	11.55
100	75482000	5032100	115.52

Area can be reduced by using chemical conditioning or by using covered beds.

Costs:

Plant Size (MGD)	Area (1000 ft^2)	Costs* (1971$)	Costs (1975$)
1	50.3	60000	90500
10	503.2	550000	828800
100	5032.1	7500000	11302000

*from Figure 18

Costs include costs of normal excavation, piping for sludge distribution, sand and gravel drainage beds and underdrain collection piping.[9]

Capital Energy Requirements:

- Beds

The drying area is partitioned into individual beds, about 20 ft. wide by 20 to 100 feet long, of a convenient size so that one or two beds will be filled by a normal withdrawl of sludge from the digesters. The interior portions are usually two or three creosoted planks one on top of the other, to a height of 15 to 18 inches stretching between slots in precast concrete posts. The outer boundaries may be of similar construction on earthern embankment for open beds, but concrete walls are required if the beds are to be covered.[26]

Plant Size (MGD)	Area (ft^2)	Length* (ft)	Total Length	Concrete (ft^3)	Vol.** (yd^3)
1	50321	224.3	897	897	33.2
10	503210	709.4	2837.5	2838	105.0
100	5032100	2243.2	8972.9	8973	332.0

*beds assumed to be square for easy calculations

** volume of concrete was determined using a single wall 0.5 feet thick and 2.0 feet deep.[26]

- Removal Requipment

Dried sludge will be removed using front-end loaders.

Plant Size (MGD)	Sludge* Vol. (ft^3/day)	Loaders Req'd** No. and Vol.	Wt. of Loaders (lbs)	(tons)
1	64.4	1 at 1.0 yd^3	16200	8.1
10	644	1 at 1.5 yd^3	16900	8.45
100	6440	3 at 5.0 yd^3	132000	66.00

Operation (hrs/day)
1.5
8.0
8.0

*assuming 50 % solids

** based on a 30 minute cycle or 16 loads per 8 hr day operating at 80 % efficiency (from Caterpillar handbook)

- Energy

Plant Size (MGD)	Concrete (yd^3)	Steel (tons)	Capital Energy (BTU x 10^6) (Concrete)*	(Steel)**	(Total)
1	33.2	8.10	15	292	307
10	105.0	8.45	46	304	350
100	332.0	66.00	145	2376	2521

*based on 437,500 BTU/yd^3 of concrete

** based on 36 x 10^6 BTU/ton of steel.

Operating Power and Labor:

Plant Size (MGD)	Power (Hp-Hr/day)*	(kwh/day)**	Labor ‡ (hrs/yr)
1	120	89.5	1750
10	640	477.3	17500
100	2080	1551.1	175000

*based on engine horsepower of the loaders operating at 16 loads/day and at 80% efficiency. (from Caterpillar Handbook).

** based on 1 hp-hr = 0.7457 kwhr

‡ based on 8 hours per machine used.

VACUUM FILTRATION

Assumptions:

Surface areas range from 50 to 300 ft^2

Yield = 4.0 $lb/ft^2/hr$ for mixed primary and waste activated sludge.

2068 lb/day/10^6 gallons treated = 86.2 lb/hr

$$\frac{(2068 \text{ lb/day})\ (7 \text{ days/week})}{(4 \text{ lb/ft}^2\text{/hr})\ (\text{ x hours/week})} = \text{filter area, ft}^2$$

Size:

Plant Size (MGD)	Operation (hrs/wk)	Solids (lb/hr)	Filter Area* (ft^2)
1	40	362	90.5 (N/A)*
10	100	1447.6	361.9 (72.4)*
100	168	8617.7	2154.2 (430.8)*

*if heat treatment is used for conditioning the filter yield may be about 20 $lb/ft^2/hr$ thus decrease the required filter area by 80%.

N/A - not good for flow $\leq$ 3.0 MGD

Costs:

Plant Size (MGD)	Filter Area (ft^2)	Cost* (1971\$)	Cost (1975\$)	
1	90.5	140000	211000	---
10	362	315000	475000	(191000)
100	2154	1750000	2638000	(515000)

*from Figure 14

Costs include the normal cost of the vacuum filters, auxiliary equipment, piping and structures.

Capital Energy Equirements:

Plant Size (MGD)	Filter Area (ft^2)	Filter* Drums No. and Size	Weight of Equipment* Filter (lbs)	Accessories** (lbs)	Total (tons)
1	90.5	1 at 6'	7400	2500	4.95
10	362	1 at 12'	24300	4100	14.20
100	2154	5 at 14'	131000	20500	75.75

*from reference 36

** accessories include vacuum pump and filtrate pump.

Capital‡ Energy (BTU x 10^6)	
1.80	(---)
510	(180)
2727	(510)

‡based on 36 x 10^6 BTU/ton of steel

Operating Power and Labor:

Plant Size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	52	1640
10	531 (52)	5650
100	5208 (531)	35500

*from reference 20

** from Figure 15 (will be more if sludge is hauled to landfill).

CENTRIFUGATION

Assumptions:

Feed solids = 2%

Effluent solids = 15 to 40%

Length/Diameter ratio = 2.8 to 3.2

Solids recovery = 80 to 95%

Design was based on centrifuge performance presented by manufacturing data.[37]

Size:

Plant Size (MGD)	Sludge (gal/day)	Operation (hrs/week)	Feed Rate (GPM)
1	18908	40	55.2
10	189080	100	220.6
100	p890800	168	1313.'

Cost:

Plant Size (MGD)	Feed Rate (GPM)	Cost* (1972 $)	Cost (1975 $)
1	55	280000	422000
10	221	560000	844000
100	1313	2000000	2536800

*from Figure 16

Costs include centrifuge equipment, sludge pumps and piping, sludge cake conveyors, equipment hoists, electrical facilities and enclosing structure.[9]

Capital Energy Requirements:

Plant Size (MGD)	Feed Rate (GPM)	No. of Cent at GPM	Centrifuge Weight* Each (lbs)	Total (tons)	Capital* Energy ($Btu \times 10^6$)
1	55	1 at 66	4800	2.4	86.4
10	221	1 at 220	16000	8.0	288
100	1313	9 at 150	7000	31.5	1134

*from manufacturing shipping weights[37]

** based on 36×10^6 BTU/ton of steel

Operating Power and Labor:

Plant Size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	90	1370
10	435	4200
100	4400	30000

*from Table 13

** from Figure 17

PRESSURE FILTER

Assumptions:[28]

Cake Density = 105 lb/ft^3

Cake Volume = 3.0 ft^3/chamber

Cake Thickness = 1.5 inches

Cake Length = 2.0 hours

Cake Solids = 50 % results

Loading = 1.034 tons/day/10^6 gallons

Ash Admixture Ratio = 1.5 to 1.0

Size:

Plant Size (MGD)	Sludge Load (lb/day)	Ash Load (lb/day)	Total Solids (lb/day)	Moisture* Wt. (lb/day)
1	2068	3102	5170	5170
10	20680	31020	51700	51700
100	206800	310200	517000	517000

*based on 50 % moisture

Total Cake Wt. (lb/day)	Cake** Vol. (ft^3)
10340	98.5
103400	984.8
1034000	9847.7

** based on 105 lb/ft^3 [28]

Plant Size (MGD)	Cake Vol. (ft^3)	Operation Time (hrs/day)	No.*** of Cycles	No. of Filter Chambers
1	98.5	5.7	2/day	33/day
10	984.8	14.3	6/day	82/day
100	9847.7	24	11/day	657/day

*** based on cycle length of 2 hrs with 2 hrs standby.

Cake**** Capacity (ft^3/chamber)	Chambers Required (No.)
3	16.5
12	13.7
15	59.7

**** from manufacturing data[38]

Plant Size	No. of Filters and Chambers	Filter Area (ft^2)
1	2 at 9	46
10	1 at 15	92
100	3 at 20	369

Cost:

Plant Size (MGD)	Filter Area (ft^2)	Cost* (1972$)	Cost (1975$)
1	46	138000	183000
10	92	276000	366000
100	369	1107000	1468000

*from Table 14; based on a total construction cost of $3,000/$ft^2$ of filter

costs include filters, feed pumps, building and installation.

Capital Energy Requirements:

Plant Size (MGD)	No. of Filters	Weight of Filters* Each (lbs)	Total (tons)	Capital** Energy (btu x 10^6)
1	2	2200	2.2	79.2
10	1	7600	3.8	136.8
100	3	9300	13.95	502.2

*from manufacturing data

** based on 36 x 10^6 btu/ton of steel

Operating Power and Labor:

Plant Size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	62.0	2080
10	620.4	5200
100	6204.0	26208

*based on 60 kwh/ton of sludge[28]

** based on one man per hours of operation per filter[28]

ANNUAL COSTS - STEP 4

Size (MGD)	Power (kwh/day) DB	VF	CT	PF
1	89.5	52 (-)	90	62
10	477.3	531 (52)	435	620
100	1551	5208 (531)	4400	6204

Size (MGD)	Annual Cost* DB	VF	CT	PF
1	980	569 (-)	986	679
10	5226	5815 (569)	4763	6789
100	16984	57208 (5815)	48180	67934

*based on $0.04/kwh

Size (MGD)	Labor (hrs/year) DB	VF	CT	PF
1	1750	1640	1370	2080
10	17500	5650	4200	5200
100	175000	35500	30000	26208

Size (MGD)	Annual Costs* (x 1000) DB	VF	CT	PF
1	12.4	11.6	9.7	14.8
10	124.3	40.1	29.8	36.9
100	1242.5	252.1	213	186.1

*based on $7.10/hour

Size (MGD)	Capital Cost (x 1000 $) DB	VF	CT	PF
1	90.5	211 (-)	422	183
10	829	475 (191)	844	366
100	11302	2638 (515)	25361	1468

Size (MGD)	Annual Cost* (x 1000) DB	VF	CT	PF
1	9.22	21.5	43	18.6
10	84.4	48.4 (19.5)	86	37.3
100	1151	268.7 (52.5)	258.3	149.5

*based on 8% over 20 years

Size (MGD)	Capital Energy (btu x 10^6) DB	VF	CT	PF
1	307	180 (-)	86	79
10	350	510 (180)	288	137
100	2526	2727 (510)	1134	502

Size (MGD)	Annual Cost * ($ /year) DB	VF	CT	PF
1	274.9	161 (-)	77	71
10	313	456.6 (161)	258	122.7
100	2256	2441 (457)	1015	449

*based on $0.03/kwh, 2.93 x 10^{-4} kwh/btu and amortized at 8% over 20 years.

ANNUAL COSTS OF CASES - STEP 4 *

Case 1 (Capital Cost, Power, Labor)

Size (MGD)	Annual Cost ($ /year) DB	VF	CT	PF
1	22600	33669 (-)	53686	34079
10	213926	94315 (60169)	120563	80989
100	2410484	577828 (310415)	519480	403534

*for calculations see Appendix C

The cost figures in parenthesis are for vacuum filtration if used with heat treatment.

Case 2 (Capital Cost, Power)

Size (MGD)	Annual Cost ($ /year) DB	VF	CT	PF
1	10200	22069 (-)	43986	19279
10	89626	54215(20069)	90763	44089
100	1167984	325728(58315)	306480	217434

Case 3 (Capital Energy, Power)

Size (MGD)	Annual Cost ($ /year) DB	VF	CT	PF
1	1255	730 (-)	1063	750
10	5539	6272 (730)	5021	6912
100	19240	59269 (6272)	49195	68383

APPENDIX F

REDUCTION

INCINERATION

Assumptions:

Solids loading = 2 $lb/ft^2/hr$ for mixed primary and activated

Temperature = 1400 to 1700 ^oF

Heat Requirements = 1800 to 2000 btu/lb of water

Capacity = 200 to 8000 lb/hr.

Size:

Plant Size (MGD)	Op. (hrs/week)	Solids Load (lb/hr)	Area* Req'd (ft^2)	No.* of Hearths
1	40	362	181	9
10	100	1447.6	724	8
100	168	8616.7	43085	2 at 12

*based on 2 $lb/hr/ft^2$

Costs:

Plant Size (MGD)	Area (ft^2)	Solids (tons/day)	Cost* (1972$)	Cost (1975$)
1	181	1.03	400000	530000
10	724	10.34	700000	928000
100	4309	103.40	2500000	3315000

*from Figure 20

Capital Energy Requirements:

Plant Size (MGD)	Area (ft^2)	Weight of Incin.* (lbs)	(tons)	Capital Energy** (btu's x 10^6)
1	181	33485	16.7	601.2
10	724	131044	65.5	2358.8
100	4309	797165	398.6	13450.0

*based on manufacturing data; about 185 lb per ft^2 of hearth area (ENVIROTECH)

Operating Power and Labor:

Plant Size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	603 (268)	1900
10	1242 (667)	5400
100	4932 (1644)	39000

*from Figure 22 and a power cost of $0.015/kwh

** from Figure 21

values in parenthesis are for pressure filtration used with inc.

Assuming 60% combustibles in medium quality sludge[26] then the weight of ash is 48% of the sludge weight generated; assuming 100% combustion of all combustibles ash volume = .40 (2068 lb/day) = 827 lb/day per million gallons treated.

WET-OXIDATION

Assumptions:

Pressure = 1000 to p750 psi

Temperature = 250^{o} to 700^{o} F

Residence Time = 20 to 60 minutes, 30 minutes average

Size:

Plant Size (MGD)	Sludge Vol. (gal/day)	Reactor* Vol. (gal)	No. of Reactors
1	18908	394	2 at 250 gal
10	189080	3939	1 at 4300 gal
100	1890800	39392	5 at 8000 gal

* based on 30 minute detention time

Cost:

Plant Size (MGD)	Optn. (hrs/wk)	Loading (lb/hr)	Cost* (1970$)	Cost (1975$)
1	40	362	300000	469000
10	100	1447.6	900000	1408000
100	168	8616.7	3 at 1400000	6568000

*from Figure 23

Capital Energy Requirements:

(due to reactor and heat exchanger)

Plant Size (MGD)	Reactor (gals)	Reactor* wt (lbs)	Heat Ex.* wt (lbs)	Total wt (tons)	Energy** (btu x 10^6)
1	500	2500	N/A	1.3	45
10	4300	16700	25800	21.3	765
100	40000	141400	99700	120.6	4339.8

*from manufacturing data (ENVIROTECH-EIMCO)

** based on 36 x 10^6 btu/ton of steel

Operating Power and Labor:

Plant Size (MGD)	Power* (kwh/day)	Labor** (hrs/yr)
1	610	520
10	6101	1300
100	61006	2190

*from Reference 30

** based on 0.25 manhours/shift of operation[4]

Wet oxidation combustion is about 80 to 90% complete.[26] The amount of combustibles in medium sewage is about 60%. Therefore, the weight of ash generated from each pound of sludge burned is $\frac{(40\%)(2068 \text{ lb/day})}{85\%}$ This amounts to 973.2 lb/day per million gallons treated.

ANNUAL COSTS - STEP 5

Power:

Size (MGD)	Power (kwh/day) INC	WO	Costs ($ /year)* INC	WO
1	603 (268)	610	6603 (2935)	6680
10	1242 (667)	6101	13600 (7304)	66806
100	4932 (1644)	61006	54005 (18002)	668016

*based on $ 0.03/kwh

Labor:

Size (MGD)	Labor (hrs/yr) INC	WO	Costs ($ /yr)* INC	WO
1	1900	520	13490	3692
10	5400	1300	38340	9230
100	39000	2190	276900	15549

*based on $ 7.10/hour

Capital Cost:

Size (MGD)	Cost ($) INC	Cost ($) WO	Cost ($/year) INC	Cost ($/year) WO
1	530000	469000	53980	47768
10	928000	1408000	94517	143405
100	2880000	6568000	293328	668951

*based on 8% over 20 years.

Capital Energy:

Size (MGD)	Energy (btu x 10^6) INC	Energy (btu x 10^6) WO	Cost ($/year) INC	Cost ($/year) WO
1	601	45	538	40
10	2358	765	2111	685
100	14350	4339	12847	2885

*based on $0.03/kwh and 2.93×10^{-4} kwh/btu and amortized at 8% over 20 years.

ANNUAL COSTS OF CASES - STEP 5

Case 1 (Power, Labor, Capital Costs)

Size (MGD)	Annual Cost ($/yr) INC	Annual Cost ($/yr) WO
1	74073 (70405)	58140
10	146457 (140161)	219441
100	624233 (588230)	1352516

Case 2 (Capital Costs and Power)

Size (MGD)	Annual Cost ($/yr) INC	Annual Cost ($/yr) WO
1	60583 (56915)	54448
10	108117 (101821)	210211
100	347333 (311330)	1336967

Case 3 (Capital Energy and Power)

Size (MGD)	Annual Costs ($/yr) INC	Annual Costs ($/yr) WO
1	7141 (3473)	6720
10	15711 (9415)	67491
100	66852 (30849)	671901

APPENDIX G

FINAL DISPOSAL

FERTILIZER AND SOIL CONDITIONER:

Assumptions:

Application = 10 to 20 tons dry solids/acre/year

Can be applied in cake or slurry.

Must be digested or heat treated.

Size:

Plant Size (MGD)	Solids (tons/yr)	Area* (Acres)	Vol. to be** Spread(gal/day)
1	377.4	25.2	4960
10	3774.1	251.6	49600
100	37741.0	2516.1	496000

*based on 15 tons/acre/year

** based on 5% solids concentration

Costs:

Costs will include costs of trucks to apply the sludge to the land. Cost of land is assumed to be free.

Plant Size (MGD)	Vol. (gal/day)	No.* of Trucks	Trips* per day	Capital** Cost ($ 1975)
1	4960	1	2.5	22000
10	49600	10	2.5	220000
100	496000	100	2.5	2200000

*based on 2100 gal capacity/truck and 2.5 trips/day during one 8 hour working day at 80% efficiency.

** based on $ 18,000/truck and $ 4000/tank (from manufacturer's data (Rhynard Truck Sales, Lansing, Mich.)

Capital Energy Requirements:

(Due to weight of trucks)

Plant Size (MGD)	No. of Trucks	Wt. of* Trucks (tons)	Capital Energy** (btu's x 10^6)
1	1	5	180
10	10	50	1800
100	100	500	18000

*based on truck weight of 10,000 lbs (from Rhynard Truck Sales, Lansing, Michigan).

** based on 36 x 10^6 btu/ton of steel.

Operating Power and Labor:

Plant Size (MGD)	Power (Hp-Hr)*	(kwh/day)**	Labor‡ (hrs/yr)
1	2933	2187	2920
10	29333	21874	29200
100	293333	218740	292000

*based on 220 Hp per truck operating 8 hrs a day at an average efficiency of 60%.

** based on 1 Hp-Hr = 0.7457 kwhr.

‡based on 8 hours per day.

This size of truck was chosen because bigger trucks tend to bog down. (Rhynard Truck Sales)

LAGOONING

Assumptions:

Depth = 5 feet

At least two lagoons must be provided

Solids loading = (MAX) 2.2 to 2.4 lb/yr/ft^3 use 2.2 lb/year/cu. ft.

Lagoons will be permanent lagoons (assumed)

Size:

Plant Size (MGD)	Vol. of Sludge (lb/yr)	Lagoon* Vol. (ft^3)	Lagoon** Area (ft^2)	Area (Acres)
1	754820	343100	68620	1.58 (0.63)‡
10	7548200	3431000	686200	15.75 (6.3)
100	75482000	34310000	6862000	157.53 (63.0)

*based on solids loading of 2.2 lb/year/ft^3

** based on 5.0 foot depth

‡if a reduction method is used.

Costs:

Plant (MGD)	Lagoon Vol. (1000 ft^3)	Cost* (1971$)	Cost (1975$)
1	343.1	25000	36700 (14000)**
10	3431.0	95000	139400 (50000)
100	34310.0	450000	660300 (220200)

*from Figure 11.

Costs include normal excavation, dike construction and piping.

** if reduction step is used.

Capital Energy Requirements:

The building of the permanent lagoons require no cement or steel and also requires no equipment to remove any sludge.

Even though there is no steel, concrete or brick used in the construction of the landfills there is still a considerable amount of energy used to construct the landfill. This energy was ignored to satisfy the definition of capital energy used here.

Operating Power and Labor:

Power is almost non-existant except for lighting and pumps. The lagoon itself doesn't use any power.

Plant Size (MGD)	Power Req'mts. (kwh/day)	Labor* Req'd. (hrs/yr)
1	N/A	115 (95) **
10	N/A	235 (160) **
100	N/A	1400 (550) **

*from Figure 12

** if a reduction step is used.

SANITARY LANDFILL

Assumptions:

Dried sludge or ash can be applied

2.0 foot layers daily

6.0 inches daily cover

Working face = 20 to 30^{o}

Operation time is usually an 8 hour day.

Size:

Landfill Equipment

Plant Size (MGD)	Sludge Wt.* (tons/day)	Shift (hrs/wk)	Sludge (tons/8 hr)	Equipment** Needed
1	4.14 (0.42)‡	40	5.8 (0.6)	1 crawler dozer
10	41.36 (4.14)	100	23.2 (2.3)	2 crawler dozer
100	413.60 (41.35)	168	137.9 (13.8)	3 rubber tire ldr

*based on dewater sludge at 25% solids

** from Reference 69 ( ) values are if a reduction step is used

Plant Size (MGD)	Equipment Descrip.	Flywheel* Hp	Machine* Wt. (lbs)
1	1 x crawler dozer	80 (-)	19,000 (-)
10	2 x crawler dozer	95 (80)	32,000 (19000)
100	3 x rubber tired loader	160 (95)	29,400 (32000)

*from Reference 69.

(-) means it is two small to use

Cost:

Plant Size (MGD)	Sludge Wt. (tons/day)	Capital* Cost (1972$)	Cost (1975$)
1	4.14 (.42)	35000	46500 (-)
10	41.36 (4.14)	150000	199000 (46500)
100	413.60 (41.4)	650000	862000 (199000)

*includes cost of equipment from Figure 26, if incineration is used their costs will decrease

Capital Energy Requirements:

No capital energy is used to construct the landfill since it is often made of earthen walls or just a hole in the ground.

Plant Size (MGD)	Equipment Weight (lbs)	(tons)	Capital Energy* (btu x 10^6)
1	19000	9.5	342 (-)
10	64000	32	1152 (342)
100	88200	44.1	1587.6 (576)

*based on 36 x 10^6 btu/ton of steel

( ) values are if a reduction step is used.

Operating Power and Labor:

Plant Size (MGD)	Power (hphr/day)*	(kwh/day)	Labor** (hrs/year)
1	762	568 (-)	2080 (-)
10	4524	3374 (568)	5200 (2080)
100	19200	14317 (1687)	8760 (5200)

*based on engine horsepower and an average efficiency of 60%.

** based on 1 man per machine for 8 hours.

ANNUAL COSTS - STEP 6

Power:

Size (MGD)	Power (kwh/day) FERT	LAG**	LNF
1	2187	N/A	568 (568)
10	21874	N/A	3374 (568)
100	218740	N/A	14317 (1687)

Annual Cost* FERT	LAG	LNF
23950	---	6220 (-)
239520	---	36945 (6220)
2395203	---	156771 (18473)

*based on $0.03/kwh

** due to permanent lagoons

Labor:

Size (MGD)	Labor (hrs/year) FERT	LAG	LNF
1	2920	115 (95)	2080 (2080)
10	29200	235 (160)	5200 (2080)
100	292000	1400 (550)	8760 (5200)

Annual Cost* FERT	LAG	LNF
20732	817 (675)	14768 (-)
207320	1669 (1136)	36920 (14768)
2073200	9940 (3905)	62196 (36920)

*based on $7.10/hour.

( ) if a reduction step is used.

Capital Cost:

Size (MGD)	Cost (x 1000 $) FERT	LAG	LNF
1	22	36.7	46.5 (-)
10	220	139.4	199.0 (46.5)
100	2200	660.3	362.0 (199.0)

Annual Cost* FERT	LAG	LNF
2241	3738 (1426)	4736 (-)
22407	14198 (5093)	20268 (4736)
224070	67252 (22427)	87795 (20268)

*amortized at 8% over 20 years.

( ) values are if a reduction step is used.

Capital Energy:

Size (MGD)	Energy (btu x 10^6) FERT	LAG	LNF
1	180	---	342 (342)
10	1800	---	1152 (342)
100	18000	---	1588 (576)

Annual Cost * FERT	LAG	LNF
161	---	306 (-)
1612	---	1031 (306)
16115	---	1422 (516)

*based on 2.93 x 10^{-4} kwh/btu, $0.03/kwh and amortized at 8% over 20 years.

ANNUAL COST OF CASES - STEP 6

Case 1 (Capital Costs, Power, Labor)

Size (MGD)	Annual Costs FERT	LAG	LNF
1	46923	4555 (2101)	25724 (-)
10	469247	15867 (6229)	94133 (25724)
100	4692473	77192 (26332)	306592 (75661)

Case 2 (Capital Costs and Power)

Size (MGD)	Annual Costs FERT	LAG	LNF
1	26191	3738 (1426)	10956 (-)
10	261927	14198 (5093)	57213 (10956)
100	2619273	67252 (22427)	244566 (38741)

Case 3 (Capital Energy, Power)

Size (MGD)	Annual Costs FERT	LAG	LNF
1	24111	---	6526
10	241132	---	37976 (6526)
100	2411318	---	158193 (18989)

Values in parenthesis are for use with a reduction step.

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