HEAT UTILIZATION IN A SEWAGE DISPOSAL PLANT

by

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SYNOPSIS

The purpose of this paper is to set forth some methods of utilizing the available energy in a sewage disposal plant with consideration of the most economical method.

A hypothetical city was selected with an equivalent population of one million and the approximate weather conditions found in the Willamette Valley. The purpose of selecting a city of such large population was to facilitate use of such innovations as the heat pump and dual fuel engines, which would not be possible with a small supply of energy, nor would the small city be financially able to employ the men with training for operating such equipment.

Many assumptions have been made based on material found in texts, journals, and papers for the reason that specific values were not available. Approximate costs of equipment and appurtenances were obtained from the manufacturers when possible.

INTRODUCTION

Remains of sanitary sewers have been found in the ruins of ancient historic cities of Assyria and Crete. Rome, also, had sewers, but they were primarily storm sewers. The refuse of humans was thrown into the streets and storms served to carry the wastes away.

No construction of sewage systems was made during the Middle Ages. As late as 1850 no human nor household wastes were allowed to be discarded into the English storm sewers. Eventually sewers were used to carry away human wastes, and these were treated as much of our sewage of today is treated, that is, by dilution.

Dilution is introducing the wastes into a body of water such as a stream, river, lake, or ocean where there is available oxygen to allow aerobic bacteria to reduce the organic matter to relatively stable compounds.

In modern times, because of increases in population and industrial growth, the streams and rivers have been overloaded with wastes to the extent that in many there remains no dissolved oxygen and natural absorption of oxygen is not rapid enough. This results in anaerobic bacterial attacking the organic material with resulting odors and unsightly conditions.

The results of overloading a body of water, besides odor and unsightly conditions, are lowered real estate values, curtailed industries, stoppage of sport and commercial fishing, and pollution of drinking water. By treating sewage, pathogenic bacteria and putrescible organic materials are transformed into stable compounds.

It is becoming evident from recent legislation in many parts of the country, including Oregon, that all cities and industries that are releasing raw wastes directly into our natural waters soon must treat the wastes before discharge. Depending upon location, nature, and course of the body of water into which the wastes are discharged, certain requirements will be made to govern the quality of the effluent. The type of plant constructed to treat the sewage will be dictated to some extent by this decision.

Any body of water freely exposed to the atmosphere will soon become saturated with oxygen for the particular partial oxygen pressure and temperature existing. Under average conditions this will mean that unpolluted water will contain from six to twelve parts per million dissolved oxygen, the oxygen content varying primarily as the temperature varies. The oxygen dissolved in the water can be used by bacteria to supply the oxygen necessary in metabolizing the organic matter contained in sewage mixed with the water. To illustrate, if the microorganisms required 100 parts per million of oxygen to oxidize the organic materials in a given sewage, that is, render the sewage stable, and this sewage was mixed equally with a water containing only ten parts per million dissolved oxygen, there would be an inadequate amount of available dissolved oxygen in the mixture to enable the microorganisms to completely oxidize the organic matter. On the other hand, if one part of sewage was mixed with ten parts of water, there would be theoretically just enough dissolved oxygen in the mixture to enable the bacteria to make use of all the organic material or to stabilize it.

Methods are available for determining both the oxygen required by microorganisms for stabilizing a given sewage and the oxygen content of any body of diluting water. From such information it is possible to calculate, with a fair degree of accuracy, the ability of any body of water to take care of sewages of different compositions. There are, of course, many other factors that will also have to be taken into consideration, such as flow characteristics and minimum rates.

The probable solution of this problem is to allocate a certain percent or amount of the available oxygen content of the body of water used as the diluent to each city and industry. The city would then have to treat the sewage in some manner to reduce the organic material in the effluent to at least the maximum amount allowed.

The sewage disposal plant is designed to reduce the organic material to acceptable limits in the most economical manner. In general there is a primary treatment plant and a secondary treatment plant. The primary plant simply separates from the sewage the settleable solids, which in most cases contain the

the greatest amount of organic material, and discharges the liquid. The solids, which are contained in the sludge, are usually placed in a covered digester and anaerobic bacteria digest the organic material. After digestion the material is dewatered by drying or filtration and either used as fertilizer or disposed of by burning or dumping. The secondary treatment plant follows a similar plan for the sludge, but the liquid is also treated to reduce its organic content. This is accomplished by aerobic bacteria, and various methods are used to supply the needed oxygen.

The following outline (7, p.192) briefly indicates the well-known methods.

Practical methods of sewage disposal may be classified as follows:

A. Without treatment:

1. By dilution

2. By irrigation

B. With treatment by one or more methods or combination of methods:

1. Separation of solids and liquids

a. Floating and coarse solids

(1) By screens

(2) In skimming tanks

b. Heavy solids

(1) By grit chambers

c. Coarse and fine suspended solids

(1) By sedimentation

(a) Plain sedimentation

(b) Chemical flocculation followed by sedimentation

(c) In cesspool

(d) In septic tank

(e) In two-story tanks

(f) Flocculation by activation followed by sedimentation

2. Treatment of liquid:

a. By oxidation through aerobic bacterial action

(1) Through dilution

(2) Through irrigation

(3) Through intermittent sand filtration

(4) Through contact beds

(5) Through trickling filters

(6) Through activation

b. By disinfection

3. Disposal of effluent:

a. By dilution

b. By irrigation

4. Treatment of solids:

   a. By digestion through anaerobic bacterial action

      (1) In septic tank

      (2) In Imhoff tank

      (3) In separate digestion tank

   b. By dewatering without digestion

      (1) By natural drying

      (2) By artificial drying

5. Disposal of undigested solids:

   a. By burning

   b. As fertilizer

The efficiency of various types of sewage treating plants can be seen in Table 1 (7, p.211).

From Table 1 it is possible to select several types of plants that serve the specific requirements of a city after a preliminary survey has been made to determine the extent of treatment required. Care must be taken in the selection to choose a treatment plant that can be expanded to fit future requirements, has a low initial cost, and low operating cost. There are other limiting factors such as available area, odor nuisance, appearance, lack of diluting medium, and funds available.

In recent years the advent of garbage disposal units (grinders) in homes has served to increase the organic load tremendously. Design of treatment plants must allow for this increase in solid matter by allowing for orderly expansion of

Table 1

Method	Percentage removal of suspended solids	Gallons sludge per million gal. sewage	Percentage removal		
			Bacteria	BOD	O_2 consumed
Plain sedimentation	40-95	1000-5000	40-75	30-35	--
Chemical precipitation	75-95	3000-10000	80-90	60-80	--
Septic tank	40-75	500-1500	40-75	25-65	--
Imhoff tank	35-80	250-750	40-75	25-65	20-50
Intermittent sand filter	95-98		98-99+	70-96	70-95
Contact bed	55-90		50-75	60-80	30-55
Trickling filter	0-80	250-750	70-85	60-90	35-60
Activated sludge	70-97	10000-30000	95-99+	70-96	50-85

facilities or possible overloading of existing equipment.

The hypothetical sewage disposal plant selected for this paper to exemplify this discussion is of the activated sludge type. This type was selected because it produces a greater amount of sludge than any other, causing the problem of heating the sludge to be exaggerated. Compressed air or mechanical agitation must be used in the aeration tanks which increases the power requirements.

The activated sludge plant is preferred at present over other types in large cities, despite the high operating costs when complete treatment is required (21, p.585). See Figure 1 for typical flow diagram.

FLOW DIAGRAM OF AN ACTIVATED SLUDGE PLANT

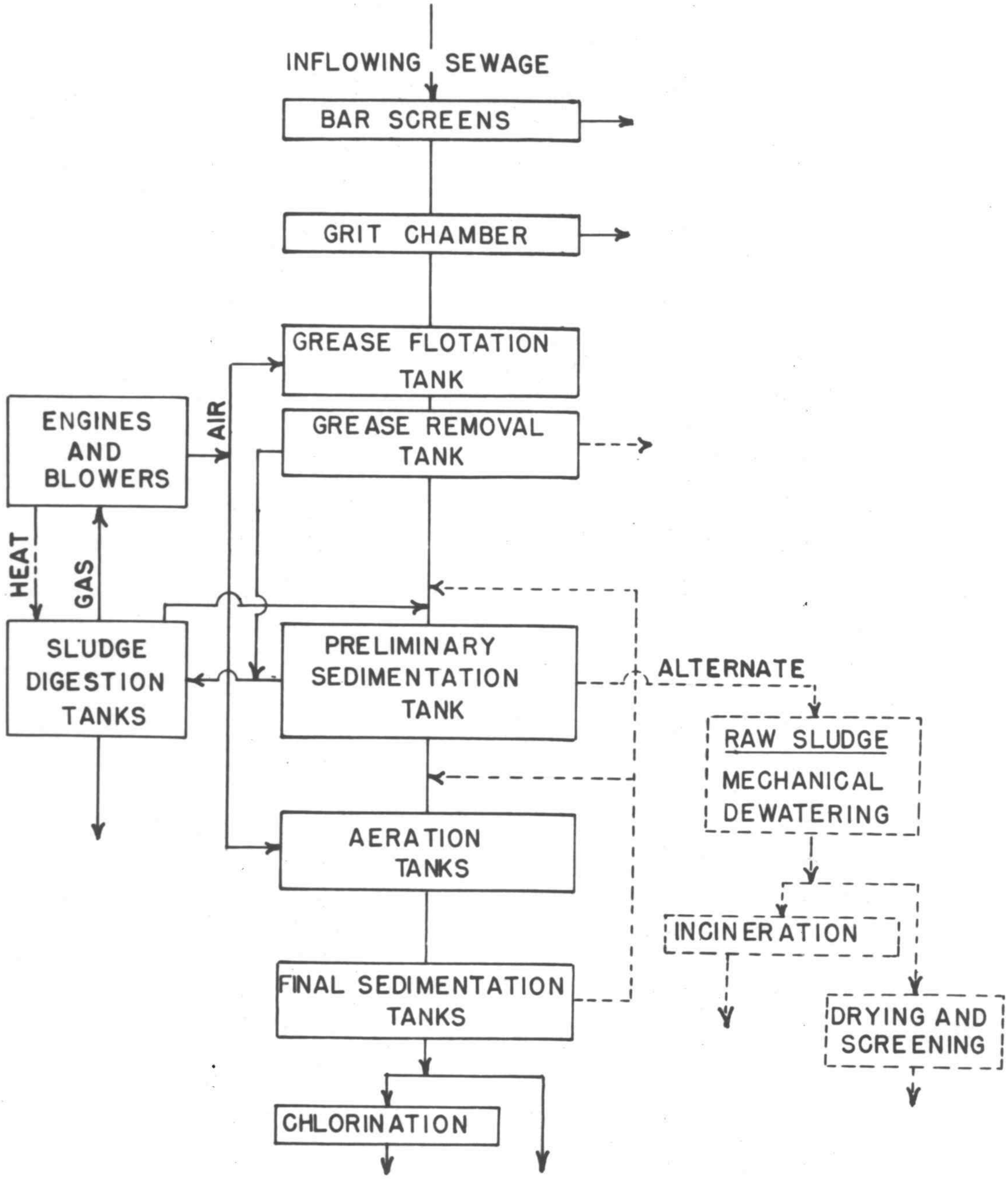


FIGURE I

GENERAL DATA AND DESCRIPTION OF PLANT

Population served (equivalent) . . . 1,000,000.

<u>Total Sewage Flow</u>

100 gallons/day/person

100 x 1,000,000 = 100,000,000 gallons/day

= 100 mgd .

<u>Digester Capacity</u>

3 cubic feet/capita (19, p.5.56)

3 x 1,000,000 = 3,000,000 cubic feet .

<u>Sludge</u> (amount per day based on 0.15 cubic feet per day per person) (24, p.R217)

1,000,000 x 0.15 = 150,000 cu ft/day

$$\frac{250,000}{24} = 6,250 \text{ cu ft/hr} .$$

<u>Gas Production Based on One and One-Quarter Cubic Feet Per Capita Per Day</u>

$$\frac{(1,000,000)(1.25)}{24} = 53,000 \text{ cu ft/hr} .$$

Average Heating Value of Gas (1, p.32)

Higher Heating Value (HHV) = 690 Btu/cu ft

Lower Heating Value (LHV) = 621 Btu/cu ft .

Gross Heating Value Available

$$690 \times 1{,}250{,}000 = 863{,}000{,}000 \text{ Btu/day}$$

$$\frac{863{,}000{,}000}{24} = 35{,}950{,}000 \text{ Btu/hr}.$$

Power Consumption

14 kw-hr/million gallons for compressed air (19, p.5.54)

8 kw-hr/million gallons for general plant power requirements

Assuming a 10 ft lift for the sewage either from the sewer or to the outfall,

$$\frac{100{,}000{,}000 \times 8.34 \times 10}{24 \times 60 \times 33{,}000} = 175 \text{ hp required.}$$

Assuming that the efficiency of pump and motor is 70 percent,

$$\frac{175 \times 0.746}{0.70} = 187 \text{ kw}$$

$$\frac{187 \times 24}{100} = 44.9 \text{ kw-hr/million gallons}.$$

Total Power Requirements

$$14 + 8 + 44.9 = 66.9 \text{ kw-hr/million gallons}.$$

Size and Number of Digesters

Assuming the plant to consist of nine digesters for flexibility in operation, the size of each digester would be $\frac{3{,}000{,}000}{9} = 333{,}000$, or approximately 340,000 cubic feet. This volume would be contained in circular digesters of 120 feet diameter with a sewage depth of 30 feet.

The heating load of the digesters will be a maximum during the winter months. A reduction of digester temperatures will reduce, or entirely halt, gas production. Therefore, the critical factors will be the temperature of the influent, desired digester temperature, and the ambient air temperature. The influent will be taken at 55 F, which is a lower temperature than recorded in winter by the Denver sewage disposal plant. Digester temperature will be 90 F (8, p.806)(7, p.200). Outside design dry bulb temperature for the Pacific Coast is normally 10 F (2, p.236,237).

The total heating load under consideration will consist of the heat required to raise the sludge to the desired temperature and the heat loss due to heat transfer through walls, cover, and floor of the digesters.

The heat required to raise the temperature of the inflowing sludge is given by the equation,

$$Q = Wc_p \Delta T .$$

Where: Q = heat required

W = weight of sludge per unit of time

c_p = specific heat of sludge (20, p.191)

ΔT = temperature difference between heated sludge and influent

$W = (\text{cu ft/hr})(\text{lb/cu ft}) = \text{lb/hr}$

$W = 6250 \times 62.35 = 390{,}000$ lb/hr

$T = (90 - 55) = 35$

$Q = (390{,}000)(1)(35) = 13{,}650{,}000$ Btu/hr

The heat loss due to heat transfer through the walls, Figure 2, is given by the following equation:

$$Q = UA\Delta T.$$

The coefficient of heat transfer, U, the units of which are Btu per hour per degree Fahrenheit per square foot of surface area, is determined for each type of cross section by the following equation:

$$U = \frac{1}{\frac{1}{f_o} + \frac{x}{k} + \frac{1}{a} + \frac{1}{c} + \ldots} \text{ Btu/hr F sq ft (2, p.112),}$$

where: f_o = surface film coefficient for outer walls exposed to air

x = thickness of the material in inches

c = conductivity for specific materials Btu/hr F sq ft

a = conductivity of air space (including film coefficients)

$f_o = 6.0$

A = area of heat transfer surface

ΔT = temperature difference in degrees Fahrenheit between sludge and outside drybulb temperature

k = conductivity coefficient in Btu/hr F sq ft/in.

$k_{concrete} = 12.00$

$k_{concrete\ with\ light\ weight\ aggregate} = 0.7$

$k_{brick} = 5.00$

$k_{concrete\ block} = 0.53$, with fill of zonolite 0.38

$k_{\text{mild steel}} = 312$

$k_{\text{wood sheathing}} = 1.02$

$k_{\text{composition roofing}} = 6.50$

$k_{\text{earth}} = 7.0$ (approximate)

A schematic drawing, Figure 2, indicates the general shape and construction of a digester with a floating cover.

The exposed wall cross section consists of eight inches of concrete, a two-inch air space, and eight inches of brick. The heat transfer coefficient U is:

$$U = \frac{1}{\frac{1}{f_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{1}{c}}$$

$$= \frac{1}{\frac{1}{6} + \frac{8}{12} + \frac{8}{5} + \frac{1}{1.1}}$$

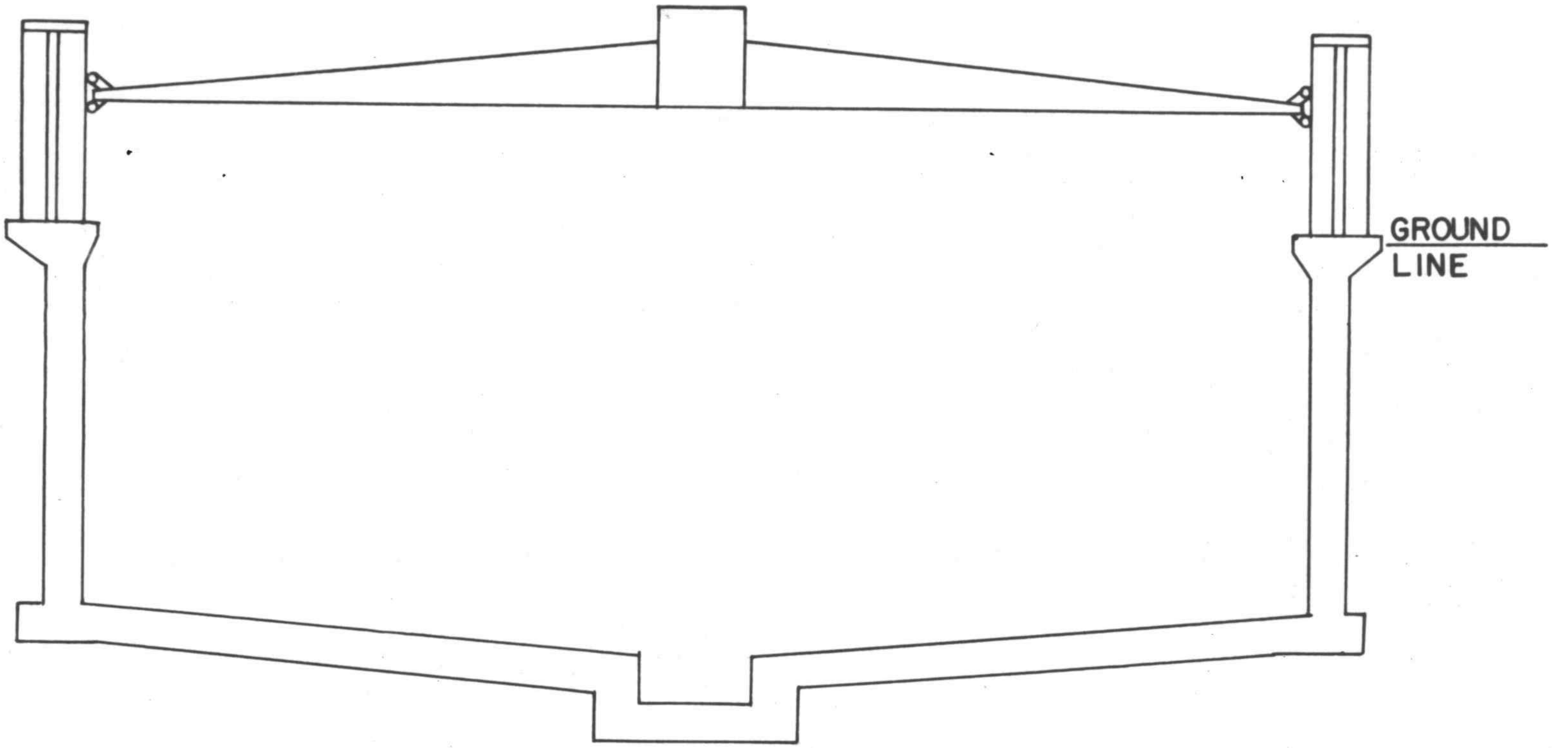
$$= \frac{1}{0.167 + 0.667 + 1.6 + 0.91} = \frac{1}{3.34} = 0.3 \text{ Btu/hr F sq ft} .$$

The cover cross section is one-quarter inch steel plate, air space, seven-eighths inch wood sheathing and asphalt roofing.

$$U = \frac{1}{\frac{1}{f_o} + \frac{1}{c} + \frac{x_1}{k_1} + \frac{1}{c} + \frac{1}{c}}$$

$$= \frac{1}{\frac{1}{6} + \frac{1}{1.1} + \frac{1/4}{312} + \frac{1}{1.02} + \frac{1}{6.50}}$$

$$= \frac{1}{0.167 + 0.91 + 0.98 + 0.54} = \frac{1}{2.6} = 0.385 \text{ Btu/hr F sq ft} .$$



SCHEMATIC SKETCH OF SLUDGE DIGESTION TANK

FIGURE 2

The value of U for the floor is 0.1 Btu/hr F sq ft, and the covered wall has a U of 0.2 Btu/hr F sq ft (10, p.380,381).

The area of the cover and bottom of the digester will be assumed equal to that of flat construction.

$A = \pi r^2$

$= (3.1416)(60)^2 = 11,320$ sq ft .

Area of wall exposed to air,

$A = \pi Dh$

$= (3.1416)(122)(10) = 3840$ sq ft .

Area exposed to ground,

$A = \pi Dh$

$= (3.1416)(121.3)(20) = 7630$ sq ft .

No calculation will be considered for variation of ground temperature due to frost line and water table. The reason for ignoring the presence of a possible water table above the depth of the digester is that good practice would allow for drainage tile to reduce heat loss and prevent upheaval if the digesters were drained for some purpose.

Heat loss through cover,

$Q = UA\Delta T$

$= (0.385)(11,320)(80) = 348,000$ Btu/hr .

Heat loss through floor,

$Q = UA\Delta T$

$= (0.1)(11,320)(45) = 51,000$ Btu/hr .

Heat loss through double wall (exposed to ambient air),

$Q = UA\Delta T$

$= (0.3)(3840)(80) = 92{,}300$ Btu/hr .

Heat loss in wall under ground,

$Q = (0.2)(7630)(45) = 68{,}700$ Btu/hr .

Total Heat Loss

Cover	348,000
Exposed wall	51,000
Covered wall	92,300
Floor	68,700
	560,000 Btu/hr/digester

560,000 x 9 = 5,040,000 Btu/hr .

Heat required for new sludge	13,650,000
Heat loss due to heat transfer	5,040,000
	19,690,000 Btu/hr

It may be noted that data used in some articles (15, p.291) (3, p.292), show that the heat required to raise the sludge temperature to the desired degree is less than twenty percent of the total heat required. This conclusion might be questioned and found erroneous, probably because the insulating effect of the earth is disregarded. Research work (10, p.380,381) has shown that the loss by conduction to earth is very small. The pertinent fact is that the concrete is merely a container and has a higher conductivity than the surrounding earth. Rather than determine the distance from the concrete at which the earth temperature has not been affected, a value for U of 0.01 Btu/hr F sq ft, recommended by the American Society of Heating and Ventilating Engineers, was used for the floor. The wall coefficient, as suggested, was 0.20 Btu per square foot hour degree Fahrenheit. The reason for the higher value is that the upper wall is near the ground surface. The values for U are approximately one-tenth the nominal figures of concrete when disregarding the earth's insulating effect.

It may be interesting to note the results of solving for the dimensions of a digester of similar construction to the type used in the problem to allow minimum heat loss.

Let H = total height

D = diameter of digester

V = volume of digester

2/3 H = depth covered by earth

The heat loss will be proportional to the temperature difference and heat transfer coefficient. Using the values previously determined,

Cover	(0.385)(85) = 34
Exposed wall	(0.3)(85) = 25.5
Covered wall	(0.2)(50) = 10
Floor	(0.1)(50) = 5

$$\text{Loss} = \frac{(\pi D^2)}{(4)}(34 + 5) + 1/3\ \pi DH\ (25.5) + 2/3\ \pi DH\ (10)$$

$$= \frac{39\pi D^2}{4} + 15.17\ \pi DH$$

$$V = \frac{\pi D^2 H}{4} = \text{constant}$$

$$H = \frac{4V}{\pi D^2}.$$

Substituting,

$$\text{Loss} = \frac{39\pi D^2}{4} + 15.17\ \frac{\pi D 4V}{\pi D^2}$$

$$= 9.75\ \pi D^2 + 60.68\ \frac{V}{D}$$

$$= 30.7\ D^2 + 60.68\ VD^{-1}.$$

Differentiating and setting equation equal to zero,

$$\frac{dh}{dD} = 61.4\ D - \frac{60.68\ V}{D^2} = 0$$

$61.4\ D^3 = 60.68\ V.$ But $V = \frac{\pi D^2 H}{4}$,

therefore,

$$D^3 = 99\ \frac{\pi D^2 H}{4}$$

$$D = .78\ H$$

or $D = 69$ ft and $H = 89$ ft for a volume of 340,000 cubic feet.

The results do not correspond to the general practice of large diameters and shallow depths. The designers are evidently designing for minimum cost of construction and the desire to prevent stratification of the materials in the digester. Results of the above solution do not vary materially when the usual values of heat loss through floors and walls in contact with the earth are used.

The cost elements of any project consist of first cost, interest on investment, operating expense, and depreciation. The annual expense calculated from these items, therefore, would indicate the equipment or plan that would be the most desirable from a financial standpoint.

The equation for annual expense incorporating the first cost, interest on money invested, operating expense, and depreciation, is as follows: (21, p.628)

$$E = Cr + \frac{Cr}{(1 + r)^n - 1} + O \, ,$$

where: E = annual expense

C = initial cost

r = rate of interest

n = life of equipment

O = operating expense (annual)

The interest rate will be considered at 3.0 percent compound interest. Lower rates are obtainable at the present time for cities in good financial condition, but the selected figure is representative. Equipment life was determined from the depreciation schedule of the United States Bureau of Internal Revenue (4, p.187). "First cost" of the various equipment was obtained from manufacturing companies when possible, and include installation cost. However, at best the cost is only approximate. Operating expense is the cost of maintenance derived from various reports and papers on actual equipment. No attempt has been made to equalize or estimate the different amount and quality of labor required for the operation.

In the case of engines and electrical motors, which are interchanged in the problem, costs will be estimated. The motors and other equipment that are common to all variations, will be neglected in comparing the relative costs.

The direct steam injection system, since it entails a minimum of piping and equipment, will be considered as part of the installation cost of the heat-producing equipment. The inside coils and unit heat exchangers will be treated in the same manner as other equipment.

The gas domes, flame arrestors, and use of floating covers to recover the sludge gas is justified to avoid nuisance and danger (6, p.424). Therefore, they will not be considered as an additional cost.

The values assumed for the cost and sale price of electricity and gas were based on local conditions. In the case of a manufactured gas plant, such as supplies gas in the Willamette Valley, the gas manufactured is considered to be free of cost in the holders--the cost having been written off by sale of by-products, thus the resultant low revenue obtained from the sale of gas by the sewage disposal plant.

It is also assumed in this problem that any gas sold will be passed through the gas utility's purifiers and scrubbers to remove any impurities. This would restrict the location of the sewage disposal plant to the vicinity of the gas works. The gas would probably not be purchased under any other conditions.

ANNUAL COST OF OPERATION USING VARIOUS METHODS AND SOURCES OF ENERGY

Case 1. Purchase electricity, generate steam in boiler for required heat, sell excess gas, use direct steam injection, and electric motor drive for blower and pumps.

Purchased power

67 kw-hr/million gallons sewage

$$\frac{(67)(100)}{34} = 303 \frac{\text{kw-hr}}{\text{hr}} .$$

Rate of 6 mills per kw-hr

$$(0.01)(303) = \$1.82/\text{hr}.$$

Heat supplied by low pressure boiler and direct steam injection into sludge.

Approximate cost of installation

$140/boiler horsepower

$$\frac{19,690,000}{(33,479)} = 588 \text{ boiler hp}$$

$$(588)(140) = \$82,300 \text{ cost of installation.}$$

Amount of gas required, assuming sixty percent combustion efficiency

$$\frac{19,690,000}{(690)(0.60)} = 47,500 \text{ cu ft gas/hr} .$$

Surplus gas

$$52{,}000 - 47{,}500 = 4{,}500 \text{ cu ft/hr}$$

$$\frac{4{,}500}{1000} \times 0.20 = \$0.90/\text{hr}.$$

Depending upon the exact description of the sewage disposal plant and the local conditions, varying methods of sludge and rough garbage disposal may be used. Incinerators may be supplied with gas instead of other fuels. Sludge may be burned, dried, buried, or disposed of in a nearby body of water. For the purpose of this paper to facilitate calculations, the excess gas and/or heat will be considered as sold to utilities. In effect, this method would be charging the costs against the operational expenses of other parts of the sewage disposal plant not under consideration.

Initial cost of motor drive for blower

60 hp	\$900

Initial cost of pump motor

250 hp	\$3750

Maintenance of boiler (based on two-thirds of initial cost in twenty years)

$$\frac{(82{,}300)(0.67)}{20} \quad \$2760/\text{year}.$$

Maintenance on motors - negligible

Total initial cost	\$86,950
Life (boiler and motors)	20 years
Maintenance	\$2760/year

$$E = Cr + \frac{Cr}{(1 + r)^n - 1} + 0$$

$$= (86,950)(.03) + \frac{(86,950)(.03)}{(1.03)^{20} - 1} + 2760$$

$$= 2610 + \frac{2610}{.805} + 2760$$

$$= 2610 + 3240 + 2760 = \$8610.$$

Annual operating expense	$ 8,610
Cost of power purchased (1.82)(8760)	15,950
Gross cost per year	24,560
Revenue from excess gas (0.90 x 8760)	7,884
Net cost per year	$16,676

Case 2.

The dual fuel engine has been installed in several sewage disposal plants and industries. It operates on the diesel cycle with either gaseous or liquid fuel. For the reason that the compression ratio is higher than spark ignition engines, the efficiency is considerably higher. Maintenance expenses are lower due to no spark ignition system.

Sewage gas alone will not ignite in the dual fuel engine. It is necessary to supply diesel oil in the amount of five to ten percent of the heating value of fuel required. It is possible to operate the engine with any ratio of diesel fuel from the minimum five percent to one hundred percent.

For the above reason dual fuel engines are particularly adapted to the sewage disposal plant because they can be operated on diesel fuel before the digesters commence to produce gas.

The heat recovered from the cooling water and exhaust gases serve to heat the sludge, which hastens the process. The immediate availability of power in plants removed from electric lines and commercial gas transmission lines by any distance, results in a varying amount of capital saved, for the reason that such construction is very expensive.

Also, the fact that the dual fuel engines are not dependent upon the gas supply for operation, reduces or eliminates any flat payment for standby power. The engines employed in sewage treatment for the past several years have had excellent operating records. The shut-down time has been less than five percent (12, p.88).

The heat recovered from the dual fuel engines can be in the form of water at any temperature desired, or up to approximately fifteen pounds per square inch gage steam. The steam is made possible by placing the cooling jackets under pressure, passing the already heated water through a low-pressure boiler heated by the exhaust gases.

A comparatively recent development of Engineering Controls Incorporated called "vapor phase cooling", causes the engine cooling water to continuously operate at atmospheric boiling temperature or higher. The unit can be operated as a closed system using the heat exchanger principle to remove engine heat or the steam produced can be used directly. Using the steam directly creates the problem of treating one hundred percent make-up water.

Examples cited in the company's literature show extremely low maintenance costs. The primary reason apparently is the high operating temperatures, which prevent the condensation of corrosive gases. Operating efficiency is also increased due to the increased temperatures.

Generate electricity by use of dual fuel engines as prime movers, heat digesters with waste heat, use direct steam injection, sell excess power and heat, if any, electric motor drive for auxiliaries.

Gas available: 52,000 cu ft/hr.

Output of engines available: 7000 Btu/bhp-hr required input based on lower heating value of fuel, 7.5 percent is diesel oil (525 Btu/bhp-hr).

Gas required:

7000 - 525 = 6475 Btu/bhp-hr (non-supercharged)

6800 - 340 = 6460 Btu/bhp-hr (supercharged).

$$\frac{(52,000)(621)}{6475} = 4980 \text{ bhp}.$$

This power could be produced by four Worthington pump and Machinery Corporation EHGO-8 Engines of 1170 rated brake horsepower each for a total of 4680 bhp output.

Another possibility would be to select two non-supercharged engines as before and two supercharged engines, SHGO-6, with a rated brake horsepower of 1320. The parts would be interchangeable as they are identical except for number of cylinders, i.e., EHGO-8 description being; eight cylinders 16 x 20 inch bore and stroke and the SEHGO-6 having six cylinders and the same bore and stroke.

Total bhp = (2)(1170) + (2)(1320) = 4980 bhp .

Generator capacity = (2)(821) + (2)(928) = 3498 kw .

The advantage of using non-supercharged engines in part is that when the plant eventually faces expansion, superchargers may be installed at little additional cost to increase the capacity. This plan can also be used if insufficient funds are possessed at the time of installation.

Power generated minus power required,

3498 - 303 = 3195 kw in excess

3195 kw-hr/hr electrical energy in excess of requirements.

Assuming that power can be sold to a utility or industry for four mills per kw-hr, the revenue would be:

(3195)(0.004) = $12.78/hr .

Cost of diesel fuel required,

$$\frac{(2340)(525) + (2640)(340)}{18{,}000} = 118.2 \text{ lb/hr}$$

$$\frac{118.2}{(8.34)(0.88)} = 16.1 \text{ gallons/hr.}$$

Assuming fuel cost is \$0.10/gallon,

$$(16.1)(0.10) = \$1.61/hr .$$

Heat Reclaimed From Engine Cooling Water and Exhaust Gases.

The heat balance of the non-supercharged engines, when operating at rated capacity, is shown graphically in Figure 3. Figure 4 indicates by means of a graph the approximate heat balance at various percentages of rated capacity. The values of Figure 4 were computed for an exhaust temperature of 250 F.

The part of the total input available for waste recovery in the form of steam at ten pounds per square inch gage pressure is 44.1 percent for non-supercharged engines, and 42.9 percent for supercharged engines. (This assumes an exhaust temperature of 350 F).

$$H = (2340)(7000)(0.441) + (2640)(6800)(0.428)$$

$$H = 7,220,000 + 7,700,000 = 14,920,000 \text{ Btu/hr}$$

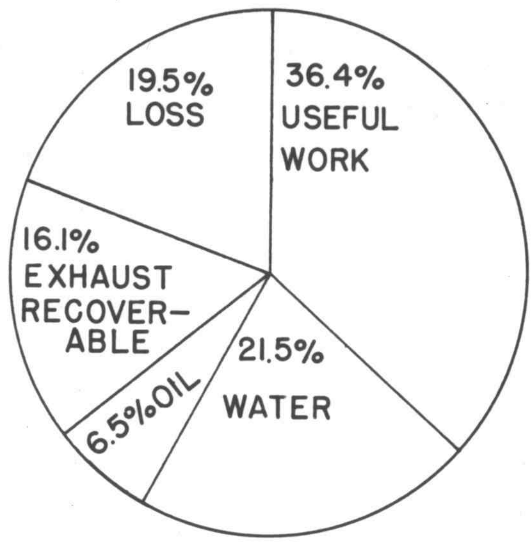
14,920,000 Btu/hr is the available heat

$$19,690,000 - 14,920,000 = 4,770,000 \text{ Btu/hr}$$

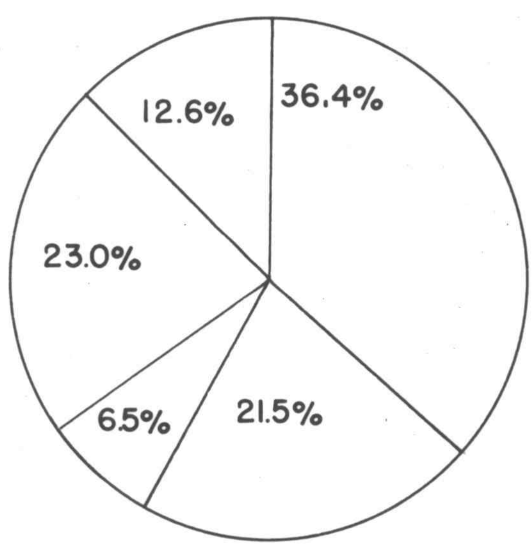
4,770,000 Btu/hr additional heat required.

The additional heat can be supplied in any manner desired. The two sources of energy that could be supplied by the sewage plant are stored gas or electricity. The gas can be collected under the floating covers to eliminate uneven gas production. If the temperature did not remain at the design conditions for a prolonged period, gas on hand could be sufficient. Electric resistance heaters could be used.

APPROXIMATE HEAT BALANCE OF TWO
NON-SUPERCHARGED DUAL FUEL ENGINES



STEAM PRODUCED FROM JACKET COOLING WATER
AND EXHAUST GASES--EXHAUST TEMPERATURE 350°F



HOT WATER SYSTEM
EXHAUST TEMPERATURE--250°F

FIGURE 3

HEAT BALANCE OF DUAL FUEL ENGINE SHOWING THE POSSIBLE DISTRIBUTION OF HEAT BASED ON THE LOWER HEATING VALUE OF THE FUEL

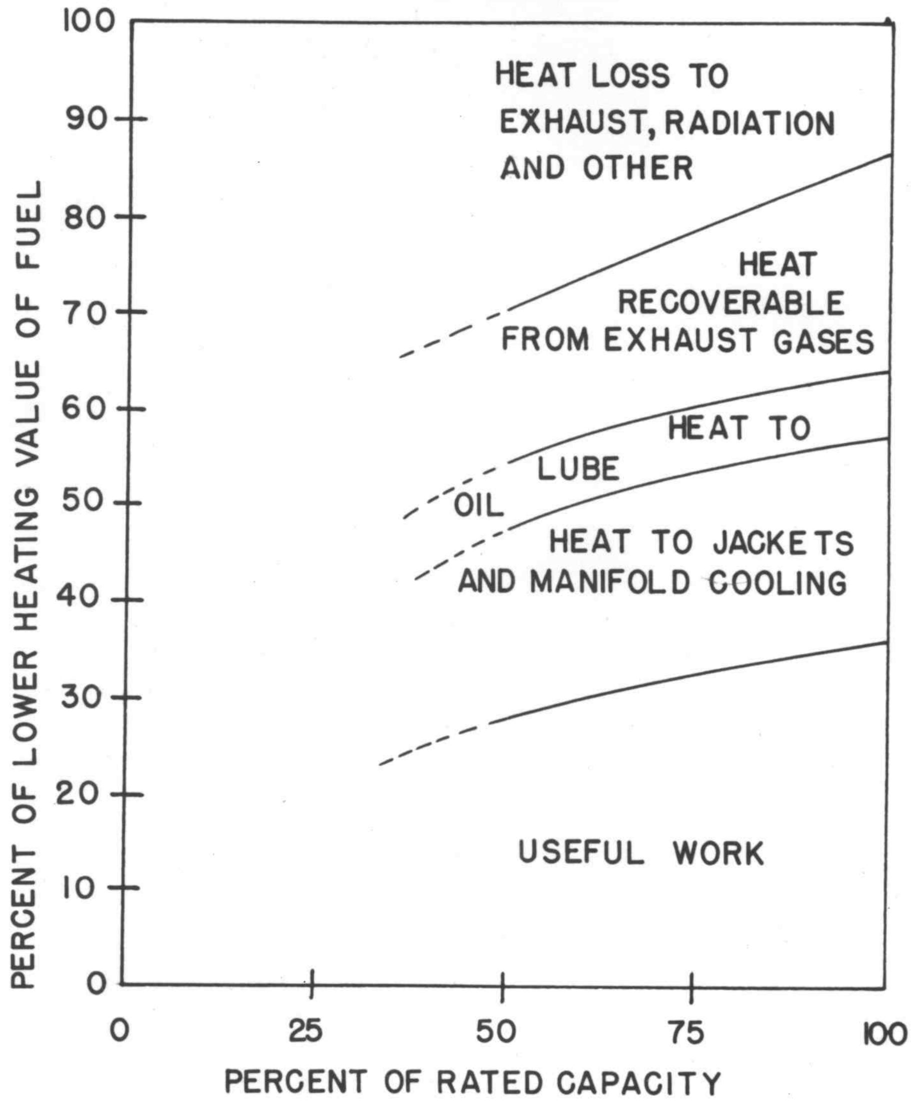


FIGURE 4

$$\frac{4,770,000}{3413} = 1380 \text{ kw-hr} .$$

1380 kw-hr would be required assuming one hundred percent efficiency. Charging the possible selling price against the plant for this heat would result in a cost of:

$$(1380)(0.004) = \$5.52/\text{hr} .$$

The unit cost of gas to equal the electrical rate would be:

$$\frac{(5.52)(0.60)(690)(1000)}{4,770,000} = 0.483/1000 \text{ cu ft} .$$

There would be a considerable saving by using gas either stored or purchased at a reasonable rate.

Assume gas is used and rate is $0.30/1000 cu ft for 690 Btu/cu ft manufactured gas,

$$\frac{4,770,000}{(0.60)(690)} = 11,500 \text{ cu ft/hr}$$

$$\frac{11,500}{1000} \times 0.30 = \$3.45/\text{hr}$$

$$\frac{4,770,000}{33,479} = 142 \text{ boiler horsepower.}$$

Let the cost be equal to $80/bhp,

$$(142)(80) = \$11,360 .$$

Maintenance,

$$\frac{(11,360)(0.67)}{20} = \$380/\text{year.}$$

The pump and blower prime movers are considered in all cases to be electric motors because of the economy of electrical drive over steam and diesel drives for small power consumption (21, p.182, 183).

Initial cost of blower motor	$ 900
Initial cost of pump motor	3,750
Initial cost of boiler	11,360
Initial cost of engine-generator sets	
Engines $80/bhp, 80 x 4980	398,400
Generators	47,500
Foundations, $60/yard (60 yards/unit)	14,400
Installation and supervision charges	10,000
Station piping and wiring	10,000
Freight	4,500
Total	$500,310

Maintenance of dual fuel engines based on $2/bhp-year (16, p.120),

(4980)(2)	9,960
Maintenance of boiler	380
Maintenance of generators and motors	Negligible
Total	$10,340

$$\text{Annual cost} = C_1r + C_2r + \frac{C_1r}{(1+r)^n - 1} + \frac{C_2r}{(1+r)^n - 1} + O$$

$$= (63{,}510)(.03) + (436{,}800)(.03) + \frac{1905}{(1+.03)^{20} - 1}$$

$$+ \frac{13{,}104}{(1+.03)^{25} - 1} + 10{,}340$$

$$= 1905 + 13{,}104 + 2365 + 12{,}000 + 10{,}340$$

$$= \$39{,}714/\text{year}.$$

Annual cost	\$39,714
Purchased gas (3.45)(8760)	30,200
Purchased diesel fuel (1.61)(8760)	14,100
Total	\$84,014/year
Revenue from sale of generated electricity, (12.78)(8760)	\$111,200/year
Net revenue	27,186/year

Case 3. Generate electricity by use of dual fuel engines as prime movers, heat digesters with waste heat, supply heat with water in coils or by use of heat exchangers, electric motor drive for auxiliaries, sell excess power and heat.

When waste heat is recovered in the form of water, the exhaust temperature can be reduced to 250 F. The amount of the heat recoverable is then fifty-one percent of the input based on the lower heating value for non-supercharged engines, and 48.1 percent for supercharged engines.

Cost of Installing Coils Over That of Direct Steam Injection Installation.

The heat transfer coefficient, U, is approximately 20 Btu/hr F sq ft for steel pipe in a digester (14, p.161),

Assume average water temperature = 130 F.

Temperature difference 130 - 90 = 40 F.

Heat transfer rate (40)(20) = 800 Btu/hr sq ft .

Heat required per digester,

$$\frac{19,690,000}{9} = 2,190,000 \text{ Btu/hr/digester.}$$

Area required,

$$\frac{2190,000}{800} = 2740 \text{ sq ft .}$$

Use three inch standard pipe (1.091 ft/sq ft outer surface),

$$\frac{2740}{1.09} = 2510 \text{ lineal feet required.}$$

Cost of coils ($1.50 per lineal foot installed),

$$(2510)(1.50) = 3760\text{/digester.}$$

Total cost (3760)(9) = $33,840.

Available heat,

$$H = (2340)(7000)(0.51) + (2640)(6800)(0.481)$$

$$= 8,350,000 + 8,630,000 = 16,980,000 \text{ Btu/hr}$$

19,690,000 - 16,980,000 = 2,710,000 Btu/hr additional heat required.

Assume use of gas-fired boiler to make up heat requirmment as in Case 2.

$$\frac{2,710,000}{(0.60)(690)} \times \frac{0.30}{1000} = \$1.96\text{/hr}$$

$$\frac{2,710,000}{33,479} = 81 \text{ boiler horsepower required}$$

$$(81)(80) = \$6480 \text{ initial cost .}$$

Maintenance on boiler,

$$\frac{(6480)(0.67)}{20} = \$217\text{/year.}$$

If the maintenance costs of the coils or unit heat exchangers are considered negligible compared to the maintenance costs of the dual fuel engines, the additional cost will be:

$$E = Cr + \frac{Cr}{(1+r)^n - 1} + 217$$

$$= (40,320)(.03) + \frac{1210}{(1+.03)^{20} - 1} + 217 = 1210 + 1500 + 217$$

$$= \$2927/\text{year.}$$

Annual cost (from Case 2)	\$39,714
Annual cost (coils and boiler)	2,927
Purchased gas (1.96 x 8760)	17,150
Purchased diesel fuel (Case 2)	14,100
Total	\$73,891/year
Revenue from sale of generated electricity, (Case 2)	\$111,200/year
Net revenue	37,309/year

Case 4. Heat supplied by electric driven heat pump, sell excess gas, electric motor drive for auxiliaries.

The heat pump has been installed successfully in many large installations, primarily in Switzerland and, comparatively speaking, recently in this country. The requisites are low power costs and a dependable source of low-level heat. In the case of the sewage disposal plant, both requirements are fulfilled as the gas is an inexpensive energy supply and the sewage flow is dependable, easily available, and generally has a greater heat content than the general low-level heat sources. The Pacific Northwest generally has electrical power for low rates, which is an alternative energy supply.

Figure 5 shows a flow diagram of the heat pump cycle and the pressure-enthalpy diagram, which is generally used in refrigeration calculations. The refrigerant chosen was trichloromonofluoromethane (F-11) because of its desirable qualities in this range of temperatures.

The compressor efficiency was assumed to be eighty percent based on adiabatic compression, the evaporator temperature, 30 F, and the condenser temperature 140 F. No superheating or subcooling of the refrigerant was considered.

Enthalpy of refrigerant in evaporator, 96 Btu/lb .

Enthalpy after adiabatic compression, 109 Btu/lb .

Work required 109- 96 = 13 Btu/lb theoretically .

Actual work $\frac{13}{.80} = 16.25$ Btu/lb .

Actual enthalpy of refrigerant after compression

$96 + 16.25 = 112.25$ Btu/lb.

Enthalpy of liquid in condenser, 33 Btu/lb .

Heat absorbed by condenser coolant

$112.25 - 33 = 79.25$ Btu/lb .

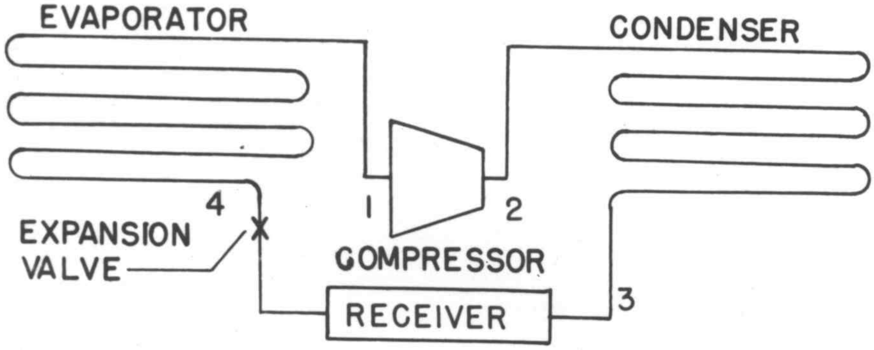
Total heat required, 19,690,000 Btu/hr

$\frac{19,690,000}{79.25} = 248,000$ lb refrigerant/hr required.

Heat absorbed by evaporator, $96 - 33 = 63$ Btu/lb

$(63)(248,000) = 15,600,000$ Btu/hr.

Capacity of compressor, $\frac{15,600,000}{12,000} = 1300$ tons.



SCHEMATIC SKETCH OF HEAT PUMP

PRESSURE-ENTHALPY DIAGRAM
OF HEAT PUMP CYCLE

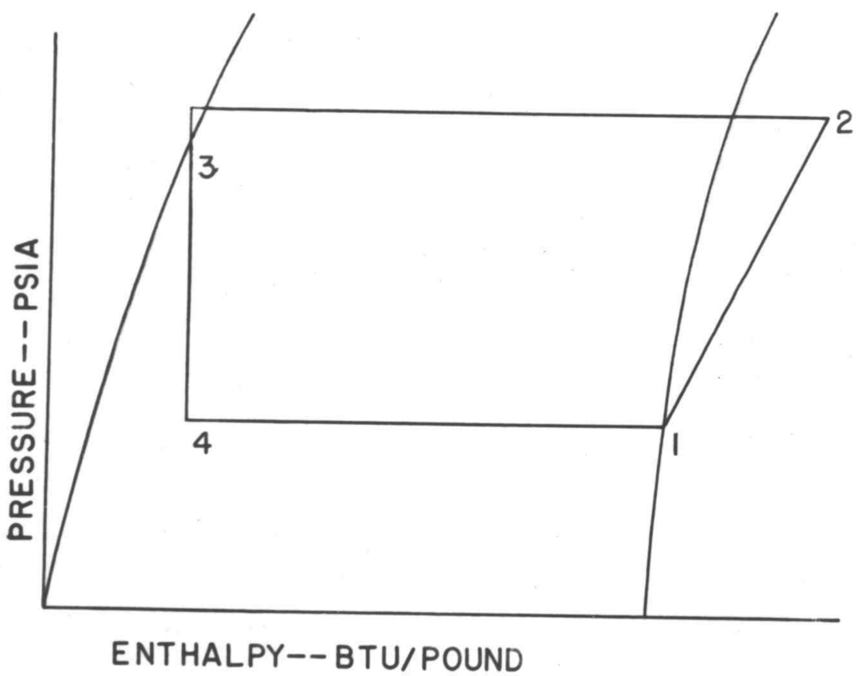


FIGURE 5

Horsepower required to operate,

$$(16.25)(248{,}000) = 4{,}030{,}000 \text{ Btu/hr}$$

$$\frac{4{,}030{,}000}{2545} = 1580 \text{ hp} .$$

Assume motor drive 90 percent efficient,

$$\frac{1580}{.90}(0.746) = 1312 \text{ kw required.}$$

Cost of electricity (6 mills per kw-hr),

$$(1312)(0.006) = \$7.87/\text{hr} .$$

Total power costs,

Heat pump motor	$7.87/hr
Blower, pump, et al (Case 1)	1.82/hr
Total	$9.69/hr

Initial cost of heat pump (based on $90/ton),

$$(1300)(90) = \$117{,}000.$$

Initial cost of motor drive ($10/hp),

$$(1580)(10) = \$15{,}800.$$

Initial cost of blower and pump motors (Case 1) = $4,650.

Maintenance - negligible.

Water temperature to 130 F,

Temperature difference 130 - 90 = 40 F

$$(20)(40) = 800 \text{ Btu/hr sq ft}$$

$$\frac{2{,}190{,}000}{800} = 2740 \text{ sq ft}$$

$$\frac{2740}{1.09} = 2515 \text{ lineal feet required.}$$

Cost, (2515)(1.50) = $3770/digester,

$$(9)(3770) = \$33{,}930.$$

Total first cost,

117,000 + 15,800 + 4,650 + 33,930 = \$171,380.

$$\text{Annual cost} = Cr + \frac{Cr}{(1 + r)^n - 1} + 0$$

$$= (171,380)(.03) + \frac{5141}{(1 + .03)^{20} - 1} + 0$$

$$= 5141 + 6380$$

$$= \$11,521/\text{year}.$$

Power cost = (9.69)(8760) = \$85,000.

$$\text{Gas} = \frac{52,000}{1000} \times 0.20 = \$10.40/\text{hr}$$

(10.40)(8760) = \$91,100/year.

Total cost,

11,500 + 85,000 = \$96,500

Revenue from

gas = \$91,100

Net cost \$ 5,400/year

Case 5. Purchase electricity, heat supplied by electric driven pump, sell excess gas, electric motor drive for auxiliaries.

In this case the calculated value of compressor tonnage could be reduced because of waste heat recovery from the dual fuel engine.

The horsepower required in Case 4 was 1580. The waste heat recovery would be fifty-one percent of the lower heating value of the fuel required.

$(1580)(7000) = 11,060,000$ Btu/hr required

$(11,060,000)(0.51) = 5,640,000$ Btu/hr recoverable.

The ratio of heat supplied by the heat pump to the recoverable heat from the diesel is,

$$\frac{19,690,000}{5,640,000} = 3.48.$$

Solving algebraically and letting x equal the heat from the diesel and 3.48x equal the heat from the heat pump,

$$x + 3.48x = 19,690,000$$

$$4.48x = 19,690,000$$

$$x = 4,390,000$$

$$19,690,000 - 4,390,000 = 15,300,000$$

15,300,000 Btu/hr required from heat pump

$$\frac{15,300,000}{79.25} = 193,000 \text{ lb/hr refrigerant.}$$

Heat absorbed by evaporator,

$(193,000)(63) = 12,170,000$ Btu/hr

$$\frac{12,170,000}{12,000} = 1013 \text{ tons.}$$

Engine required,

$(193,000)(16.25) = 3,140,000$ Btu/hr

$$\frac{3,140,000}{2545} = 1213 \text{ hp.}$$

Gas required,

$$\frac{(1213)(6475)}{621} = 12,650 \text{ cu ft/hr.}$$

Diesel fuel required,

$$\frac{(1213)(525)}{18{,}000} = 35.4$$

$$\frac{35.4}{(8.34)(.88)} = 4.83 \text{ gallons/hr .}$$

Annual cost of diesel fuel,

(4.83)(0.10) = \$0.48/hr

(0.48)(8760) = \$4240/year.

Initial cost of heat pump (\$90/ton)

(1013)(90) = \$91,170.

Initial cost of diesel (\$100/bhp to include installation cost)

(1213)(100) = \$121,300.

Initial pump and blower motors = \$4,650.

Maintenance cost (\$2 bhp/year)

(1213)(2.00) = \$2,426/year.

$$\text{Annual cost} = Cr + \frac{Cr}{(1+r)^n - 1} + 0$$

$$= (217{,}120)(0.03) + \frac{6514}{(1+.03)^{25} - 1} + 2426$$

$$= 6514 + 5980 + 2426 = \$14{,}920.$$

Total annual cost	\$14,920
Diesel fuel	4,240
Power	15,950
	35,110/year

Revenue from excess gas,

$$52{,}000 - 12{,}650 = 39{,}350$$

$$\frac{(39{,}350)(0.20)}{1000} = \$7.87/\text{hr}$$

$$(7.87)(8760) = \$69{,}000.$$

Net income,

$$\$69{,}000 - 35{,}110 = \$33{,}890/\text{year}.$$

As a matter of interest the coefficient of performance, COP, for this particular arrangement is,

$$\frac{19{,}690{,}000 \text{ Btu/hr delivered}}{(1213)(7000) \text{ Btu/hr supplied}} = 2.5.$$

This value is not a true value for the COP, however, because the necessary power for pumps is not included. The value would be small because of the low head.

The sewage, 100 mgd, temperature would be reduced,

$$\frac{100{,}000{,}000}{24} \times 8.34 = 35{,}200{,}000 \text{ lb/hr}$$

$$Q = W_{cp} \quad T$$

$$T = \frac{Q}{W_{cp}} = \frac{15{,}300{,}000}{(35{,}200{,}000)(1)} = 0.435 \text{ F} .$$

Temperature drop = 0.435 F.

<u>Case 6</u>. Boiler generates high pressure steam, turbine-generator set generates power and exhausts at 30 psig, direct steam injection used, electric motor drive for auxiliaries, excess power and gas sold.

$$\text{bhp} = \frac{(\text{cu ft gas/hr})(\text{Btu/cu ft})(\text{ efficiency})}{\text{Btu/hr/bhp}}$$

$$\frac{(52{,}000)(690)(0.60)}{33{,}479} = \frac{21{,}550{,}000}{33{,}479} = 644 \text{ boiler hp .}$$

Steam at 600 psig and 750 F

Enthalpy, 1378.9 Btu/lb

Steam rate, 25 lb/Bhp-hr

$$\frac{21{,}550{,}000}{(1379)(25)} = 625 \text{ bhp}$$

(625)(.746)(.90) = 420 kw.

Turbine cost ($18/bhp with gear)

(625)(18) = $11,250.

Generator ($15/kw)

(420)(15) = $6300.

Enthalpy 30 psig steam, 1170 Btu/lb

(625)(25)(1172) = 18,300,000 Btu/hr available

(19,690,000 - 18,300,000 = 1,390,000

1,390,000 Btu/hr additional heat required.

The additional heat can be supplied by operating the boiler of more than the rated capacity and using a pressure reducing valve to supply steam at the lower pressure.

$$\frac{1{,}390{,}000}{(.60)(690)} = 3360 \text{ cubic feet gas/hr}$$

$$\frac{(3360)(0.30)}{1000} = \$0.91\text{/hr cost}$$

(0.91)(8760) = $7880/year.

Total initial cost,

Boiler	\$125,000
Turbine	11,250
Generator	6,300
Motors	4,650
	\$147,200

Excess power,

$$420 - 303 = 117 \text{ kw}$$

$$(117)(0.004) = \$0.47/\text{hr}$$

$$(0.47)(8760) = \$4120/\text{year}.$$

Maintenance (2/3 boiler initial cost in 20 years)

$$\frac{(125,000)(.67)}{20} = \$4180/\text{year}.$$

$$\text{Annual cost} = Cr + \frac{Cr}{(1 + r)^n - 1} + 0$$

$$= (147,200)(0.03) + \frac{4416}{(1 + 0.03)^{20} - 1} + 4180$$

$$= 4416 + 5480 + 4180$$

$$= \$14,076/\text{year}.$$

Total cost of operation	\$21,956
Revenue from generated electricity	4,120
Net cost	\$17,836/year

Table 2. Summary of Results for Cases 1 to 6

Case	Initial cost	Maintenance costs per year	Annual cost	Cost of additional gas or electricity and diesel fuel/yr	Total annual cost	Revenue per year	Net cost or revenue per year
1	86,950	2,760	8,610	15,950	24,560	7,884	- 16,678
2	500,310	10,340	39,714	44,300	84,014	111,200	+ 27,186
3	540,630	10,340	42,641	31,250	73,891	111,200	+ 37,309
4	171,380	Neg	11,521	85,000	96,521	91,100	- 5,400
5	217,120	2,426	14,920	20,190	35,110	69,000	+ 33,890
6	147,200	4,180	14,076	7,880	21,956	4,120	- 17,836

The six representative cases presented are but a few of the possible combinations of equipment. It is evident from these illustrations, however, that the use of dual fuel engines, despite the high initial cost, is the most economical method to utilize the available energy.

<u>Case 7</u>.

Another approach to the reduction of costs in a sewage disposal plant is the study of bacterial action with respect to the temperature.

It has been proved by Heukelekian (9, p.219)(8, p.806), and by Fischer and Greene (5, p.718) that digestion by thermophilic bacteria is more rapid and the quality of the supernatant liquor and sludge is greater than the results of digestion by psychrophilic and mesophilic bacteria.

The reasons for not using the higher temperature required by thermophilic bacteria, 120 F, for sludge digestion, are probably because of higher heat losses and inability to heat to that high level with methods used in the past.

Until recently the primary method of heating was by warm water with the heat exchange occuring through coils suspended around the inside circumference of the digestion tanks. If the temperature of the water was elevated above 130 to 140 F, caking of sludge on coils occurred (11, p.236). It is evident, therefore, that in the winter months sufficient heat for thermophilic digestion could not be supplied. In fact, in many locations, due to sludge characteristics or plant operation, the sludge temperature drops below the optimum of 90 to 95 F for mesophilic digestion.

Another disadvantage of fixed coils in the digester arises where they must be cleaned or repaired. The sludge must be removed and stringent safety precautions must be observed to avoid explosions and possible asphyxiation of workmen.

Many new schemes for heating have been devised and tested with varying results. Some of these methods are direct steam injection (17, p.425) (18, p.24), heating coils imbedded in the concrete walls of the digester (22, p.247), vertical type coils with forced connection of sludge (14, p.54,55), outside heating elements (23, p.538), submerged gas heaters featuring direct heat exchange between hot gases of combustion and sludge (11, p.236), and direct injection of hot water (20, p.191).

Direct steam injection appears to be the most economical and efficient method for heating sludge. There appear to be no disadvantages of any importance. The heat content of steam is great enough to heat the sludge without appreciable dilution. By using pumps to recirculate and mix sludge from the digester with fresh sludge circulation in the digester is obtained and stratification is avoided. The addition of heated sludge removes any chance of thermal shock, which will stop production of gas with as small a variation as 3 F in some cases (13, p.406). The only equipment required is a mixing chamber and a header constructed of pipe to admit steam to the chamber. No caking of the sludge is possible.

The plan of placing heating coils in the walls does not appear feasible for the reason that the greatest temperature differential and therefore greatest flow of heat would be toward the outside. Caking is possible on digester walls. Possible constrictions in water lines would prove difficult to remove. Thermal circulation would not prove enough to give minimum heat transfer requirements.

The vertical type coils have one decided advantage over the horizontal coil in that they may be removed for cleaning without emptying the digester. Forced convection of sludge by paddles to maintain equal temperatures throughout and to increase the heat transfer coefficient seems to be over-rated. Tests have shown that temperature differentials of 10 F are found. Consequently, gas production and digestion of organic material is seriously hampered.

The outside heating elements have the advantage of easy accessibility, high velocities, which prevent cake formation at elevated temperatures, and higher possible sludge temperatures.

Submerged gas heaters of the open and closed types have been used in chemical processing plants for some time. The open type allows the hot combustion gases to mix directly with the medium to be heated. In the case of sludge it would not be possible to do this in the digester as the gases of combustion would mix with the sludge gas formed by digestion. The use of outside heating units is satisfactory if there are no objections to the odor of the escaping exhaust gases bubbled through the sludge.

The closed type heater is similar to other types of heat exchangers except that the exhaust gases are the heating medium. Keefer (11, p.236) claims that caking on the heating surfaces is not a problem.

Direct injection of hot water has the same advantage as steam injection except that the ratio of the amount of water injected to the heat supplied is very high and seems to be a limiting factor.

Heat Losses During Thermophilic Digestion.

Heat required to raise sludge temperature,

$$Q = Wc_p \Delta T$$

$$= (390{,}000)(1)(65) = 25{,}350{,}000 \text{ Btu/hr} .$$

Heat loss through cover,

$$Q = UA \Delta T$$

$$= (0.385)(11{,}320)(110) = 480{,}000 \text{ Btu/hr} .$$

Heat loss through floor,

$$Q = UA \Delta T$$

$$= (0.1)(11{,}320)(75) = 85{,}000 \text{ Btu/hr} .$$

Heat loss through exposed wall,

$$Q = UA \Delta T$$

$$= (0.3)(3840)(110) = 127{,}000 \text{ Btu/hr} .$$

Heat loss through lower wall,

$$Q = UA\Delta T$$

$$= (0.2)(7630)(75) = 114,500 \text{ Btu/hr} .$$

The total heat loss (based on five digesters),

480,000

85,000

127,000

<u>114,500</u>

806,500 x 5 = 4,032,500

<u>25,350,000</u>

29,382,500 Btu/hr .

The heat required to raise the sludge to 120 F from the original temperature is approximately 83 percent of the total heat required for thermophilic digestion. It does not appear feasible for that reason to insulate the digesters to save the relatively small amount of heat lost due to heat transfer.

The maximum amount of heat available at 60 percent efficiency of the boiler is (52,000)(0.60)(690) = 21,550,000 Btu/hr . 29,383,000 - 21,550,000 = 7,833,000 Btu/hr additional heat required.

Purchasing additional gas for $0.30 per 1000 cubic feet,

$$\frac{(7,833,000)(0.30)}{(0.60)(690)(1000)} = \$5.67/\text{hr}$$

$$(5.67)(8760) = \$49,700/\text{year}.$$

Boiler horsepower,

$$\frac{7,833,000}{33,479} = 234 \text{ boiler horsepower}$$

$(234)(140) = \$32,800.$

Maintenance,

$$\frac{(32,800)(0.67)}{20} = \$1100/\text{year.}$$

$$\text{Annual cost} = Cr + \frac{Cr}{(1+r)^n - 1} + 0$$

$$= (49,700)(.03) + \frac{1491}{(1+.03)^{20} - 1} + 1100$$

$$= 1491 + 1855 + 1100$$

$$= \$4446/\text{year.}$$

The values calculated are in addition to those determined for Case 1.

Case 1		\$24,569/year
Annual cost		4,446
Purchased gas		49,700
	Total	\$78,715/year

Area (120 ft dia) = $(60)^2(3.1416) = 11,310$ sq ft .

Volume (120 ft dia, 10 ft height)(exposed wall)

$(11,320)(10) = 113,200$ cu ft

(120 + 1.33 dia, 10 ft height)

$(60.67)^2(3.1416)(10) = 115,600$ cu ft

Difference = 2400 cu ft .

Volume (covered wall),

226,400 cu ft (inner volume)

234,000 cu ft (outer volume)

Difference = 7600 cu ft .

Volume floor,

11,310 cu ft .

Total concrete volume,

$$2{,}400 + 7{,}600 + 11{,}310 = 21{,}310 \text{ cu ft}$$

$$\frac{21{,}310}{27} = 790 \text{ cu yd}.$$

Cost,

(790)(90)	=	\$ 71,100	concrete
(11,310)(10)	=	113,100	cover
$\frac{(2400)}{27}(90)$	=	8,000	brick (used)
		\$192,200	

The piping, motors, flame traps and other appurtenances would make \$200,000 per digester a minimum value.

$$(200{,}000)(5) = \$1{,}000{,}000.$$

Consider a life of 50 years and no maintenance,

$$\text{Annual cost} = Cr + \frac{Cr}{(1 + r)^n - 1}$$

$$= (1{,}200{,}000)(.03) + \frac{36{,}000}{(1 + .03)^{50} - 1}$$

$$= 36{,}000 + \frac{36{,}000}{3.9} = 36{,}000 + 9230$$

$$= \$45{,}230/\text{year}.$$

The net cost per year using boilers to supply heat for thermophilic digestion is 78,715 - 45,230 = \$33,485. The value is slightly higher than the figure for mesophilic digestion, but the initial cost is considerably less.

The "net costs" and net revenues" as determined are not true values for an operating year. The amount of gas purchased is for the extremes of winter, which may or may not occur normally, but the heating capacity must be designed for these conditions. It is a fact that the amount of heat required will not vary to such a great extent in a sewage disposal plant as in the heating of buildings. The reason is that the heat loss due to heat transfer is a small part of the total heat required and the influent temperature of the sewage, which would cause the greatest change, does not vary considerably if infiltration is not exceedingly large. To illustrate this, the heat required in a summer month with an average temperature of 63 F is 24,740,000 Btu/hr for thermophilic digestion. This compares with the maximum value of 29,383,000 Btu/hr.

The average value for the year would necessarily fall between the two values. The values calculated are not entirely accurate for these reasons, but for comparison purposes are sufficient.

CONCLUSIONS

Dual fuel engines appear to be the best solution to the problem of utilizing the gas provided by decomposing sludge in sewage treatment plant digesters. The advantages of dual fuel engines are distinct. The two main advantages are immediate availability of electrical power and heat and the most economical method of utilizing the energy in the sludge gas. The reliability of these engines is excellent because no dependency on the steady supply of gas is required. The primary disadvantage is the high initial cost. The added maintenance costs and the need of skilled operators are more than compensated by the efficiency of such machinery.

The heat pump, when the dual fuel engine is used as prime mover, compares favorably from an economic standpoint with the other methods discussed. This would be true only in large installations which would justify the skilled operators needed. Greater initial costs per ton of refrigeration effect would be experienced in smaller units in case of smaller disposal plants, or when two or more units are used for flexibility in operation.

The energy required per unit heating effect would increase, i.e., lower the coefficient of performance, and thereby decrease the net revenue found for mesophilic digestion if the unit were designed for temperatures high enough for thermophilic digestion.

Thermophilic digestion, with regard to the assumptions made in this paper, would entail higher net cost per year than mesophilic digestion. However, the initial investment in the disposal plant would be considerably less than with mesophilic digestion due to the reduction in the number of digestion tanks required.

An existing plant that is overloaded could install additional heating devices at a relatively low cost and employ thermophilic digestion in lieu of building additional digestion tanks to increase the capacity. This would depend to some extent upon the present method of heat transfer. Coils in the digestion tanks used to supply heat for mesophilic digestion would not be suitable.

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