EPA-600/2-77-214
November 1977

ENERGY REQUIREMENTS FOR
MUNICIPAL POLLUTION CONTROL FACILITIES

by

G. M. Wesner

Culp/Wesner/Culp
Clean Water Consultants
Santa Ana, California 92707

Contract No. 68-03-2186

Project Officer

Francis L. Evans, III
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

In view of the worldwide energy situation, it is important that designers of municipal pollution control facilities consider the energy requirements for various control methods. This report presents information on energy requirements for various treatment processes and requirements for production of consumable materials commonly used in municipal pollution control facilities.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

EXECUTIVE SUMMARY

This report presents information on energy requirements in municipal pollution control facilities for several major areas of interest.

1. Pumping energy for filtration and granular carbon adsorption of secondary effluent - Pumping requirements are developed for all elements of the filtration process including: (a) main stream, (b) backwash, (c) surface wash, (d) wash water return, and (e) chemical feed. The estimates show that main stream pumping consumes by far the greatest part of the energy used for filtration. Energy for gravity filtration at a rate of 5 gpm per sq ft varies from about 0.028 kwh per 1000 gal in a 1 mgd plant to 0.013 kwh per 1000 gal in a 100 mgd plant. Energy for pressure filtration at a rate of 5 gpm per sq ft varies from about 0.12 kwh per 1000 gal in a 1 mgd plant to 0.08 kwh per 1000 gal in a 100 mgd plant. A lower filter rate of 2 gpm per sq ft requires more energy if it is assumed that the wash rate (15 gpm per sq ft for estimates herein) remains constant.

2. Heat Requirements - Estimated heat requirements are developed for several operations that may be used in municipal wastewater treatment plants.

    (a) Building heat. Wastewater treatment plant heating requirements are presented as a function of plant capacity for three cities: Minneapolis, New York and Los Angeles.

Treatment Plant Capacity (mgd)	Building Heating Requirements (million Btu/yr) Los Angeles	New York	Minneapolis
1	77	290	450
10	230	900	1,600
100	1,100	4,400	6,500

    (b) Anaerobic digestion. Heat requirements for anaerobic digestion at 95°F in standard and high rate digesters are given as a function of influent sludge temperature.

Influent Sludge Temperature (°F)	Digester Heat Required (million Btu/mgd)			
	North U.S.		South U.S.	
	High Rate	Standard Rate	High Rate	Standard Rate
40	4.2	5.85	3.0	3.55
70	2.35	3.95	1.8	2.3

    (c) Heat treatment of sludges. Requirements are presented for both heat conditioning prior to dewatering and for oxidation prior to ultimate disposal. Fuel requirements are given as a function of thermal treatment capacity. The effects on energy requirements of treatment of waste liquors and odors produced in heat treatment

process are discussed. Fuel requirements vary from 2.8 to 5.0 billion Btu/yr in a 10 gpm thermal treatment capacity plant. Fuel requirements vary directly with plant capacity.

(d) Lime recalcination. Fuel requirements are presented as a function of hearth area for recalcination of six different sludges in multiple hearth furnaces. Natural gas requirements vary from 14 to 120 million scf/yr for a furnace with a 1,000 sq ft hearth area loaded at a rate of 7 psf/hr.

(e) Granular carbon regeneration. The maximum total energy required for on-site regeneration of activated carbon is estimated to be 8,300 Btu per lb. This total includes furnace fuel, steam, fuel for an afterburner and a small amount of electrical energy.

3. Utilization of Anaerobic Digester Gas - It is estimated from a survey of existing installations, and data in the literature, that about 6.5 million Btu per million gallons of wastewater treated are available from gas produced by anaerobic digestion of sludge from primary and activated sludge treatment. Cost estimates are presented for cleaning and storing digester gas, and for use as fuel in internal combustion engines that are coupled to pumps, blowers or electrical generators. On-site electricity generation costs are estimated to be $0.028 per kwh in a 100 mgd plant and $0.047 per kwh in a 10 mgd plant.

4. Estimated energy requirements are presented for the off-site production of the following consumable materials used in some wastewater treatment processes:

Consumable Material	Fuel Million Btu/ton	Electricity kwh/lb
Activated Carbon	102*	4.9
Alum	2*	0.1
Ammonium Hydroxide	41*	2.0
Carbon Dioxide	2 to 54	0.1 to 2.6*
Chlorine	42	2.0*
Ferric Chloride	10	0.5*
Lime (Calcium Oxide)	5.5*	0.3
Methanol	36*	1.7
Oxygen	5.3	0.3*
Salt (Sodium Chloride)		
Evaporated	4*	0.2
Rock & Solar	0.5	<0.1*
Sodium Hydroxide (50% NaOH)	37	1.8*
Sulfur Dioxide	0.5	<0.1*
Sulfuric Acid	1.5*	0.1

*Indicates principal type of energy used in production.

This report was submitted in partial fulfillment of Contract 68-03-2186 by Culp/Wesner/Culp - Clean Water Consultants under the sponsorship of the U.S. Environmental Protection Agency.

CONTENTS

FIGURES

TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

Baumé	Bé
British thermal unit	Btu
cubic foot (feet)	cu ft
degree	o
degree Celsius	^{o}C
degree Fahrenheit	^{o}F
feet (foot)	ft
gallon (s)	gal
gallons per day per square foot	gpd/sq ft
gallons per minute	gpm
gallons per minute per square foot	gpm/sq ft
horsepower	hp
horsepower hour (s)	hp-hr
hour (s)	hr
internal combustion	IC
kilogram (s)	kg
kilowatt	kw
kilowatt-hour	kwh
milligrams per liter	mg/l
million	mil
million gallons	mil gal
million gallons per day	mgd
minute (s)	min
pound (s)	lb
pounds per square inch	psi
pounds per square inch absolute	psia
pounds per square inch gage	psig
square foot (feet)	sq ft
total dynamic head	TDH
volatile solids	VS
year (s)	yr

SECTION 1

INTRODUCTION

The total energy required to treat all wastewaters in the United States is small compared to the total national energy use. One report[1] estimates that it would require about one percent of the current energy demand in the United States to operate all of the following pollution control facilities: (1) sulfur dioxide control for power plants, (2) municipal wastewater treatment to the tertiary level, and (3) solid waste collection and disposal. Nevertheless, even though energy requirements for wastewater treatment are small compared to total national energy demands, designers and owners have become increasingly concerned with energy and chemical costs.

Still more recently, a new facet has been added to the problems of process selection in wastewater treatment plant design. The fuel shortage, which began in the winter of 1973 has made it necessary to consider not only the cost of electric power, fuel and chemicals, but also the availability of these commodities.[2] Since supplies of this nature ultimately depend heavily on the availability of crude oil or possible alternate fuels, it is essential that the treatment plant designer take into account the total energy requirements of the treatment facility under consideration so that the desired effluent standards may be achieved with the minimum practical energy consumption.

A unique tool for making preliminary estimates of capital costs and operating and maintenance costs for wastewater treatment systems exists in the form of a digital computer program[3] developed at MERL, Cincinnati. This program is ideally suited for calculating estimated total energy requirements for any selected treatment system. In order for these total energy requirements to be calculated, the energy requirements for individual treatment processes must be developed and entered into the computer program.

One objective of this study is the procurement of organized information pertaining to the total energy requirements of various wastewater treatment processes. This includes both the energy consumed at the treatment plant and the energy required, at the source, for production of the supplies and chemicals consumed in the wastewater treatment processes. Although some work has already been done by Smith[4] in estimating electrical power consumption in sewage treatment processes and in estimating fuel consumption for incineration of sludges, additional information is required.

In addition to the estimation of energy consumed in individual processes of a treatment system it is also of interest to estimate the potential for producing energy from the by-products of treatment; for example, the use of anaerobic digester gas. Digester gas, after being cleaned and stored, can be used as fuel for internal combustion engines or for supplying heat to individual processes or buildings. Internal combustion engines can be directly coupled to water pumps or air blowers or used to generate electrical power which can then be used for general in-plant use. Another alternative is to use digester gas to generate steam which can then be piped around the plant to drive water pumps and air blowers, or for various types of building and process heating. One of the major elements of this task is to estimate the cost associated with the use of digester gas in order that the in-plant use of the gas can be compared to the alternative of selling the gas to a utility.

English units are used extensively in this report because of their common use in the municipal pollution control literature. A list of English-metric unit conversion factors is included following the references.

SECTION 2

PUMPING ENERGY FOR FILTRATION AND GRANULAR CARBON ADSORPTION OF SECONDARY EFFLUENT

Energy for filtration can be estimated from the power required for water and chemical pumping:

$$TE = P + BW + SW + WWR + CF \qquad (1)$$

where
TE = total energy required
P = main stream pumping
BW = backwash pumping
SW = surface wash pumping
WWR = wash water return pumping
CF = chemical feed pumping

Power required for water pumping is given in the EPA Report by Smith [4] in the following relationship:

$$hp = \frac{Q \times 0.17546 \times TDH}{E} \qquad (2)$$

where
hp = horsepower
Q = flow, mgd
TDH = total dynamic head, ft
E = hydraulic efficiency

Electricity required for pumping is determined from equation (2) by converting hp to kw and including a time factor:

$$\text{Electricity, kwh/day} = \frac{0.746 \times T \times Q \times 0.17546 \times TDH}{E}$$

$$= \frac{0.131 \times T \times Q \times TDH}{E} \qquad (3)$$

where T = hr per day pump is operated
and Q, TDH and E are the same as before

It is necessary to estimate TDH and E to determine P; and T, Q, TDH and E to determine BW, SW and WWR.

The following criteria and estimates are used herein to calculate filtration energy:

- Efficiencies (E) of electric motors and centrifugal pumps. Overall, or wire to water, efficiencies were derived and are shown in Figure 1. Figure 1 is used to determine all hydraulic efficiencies.

- P, main stream pumping

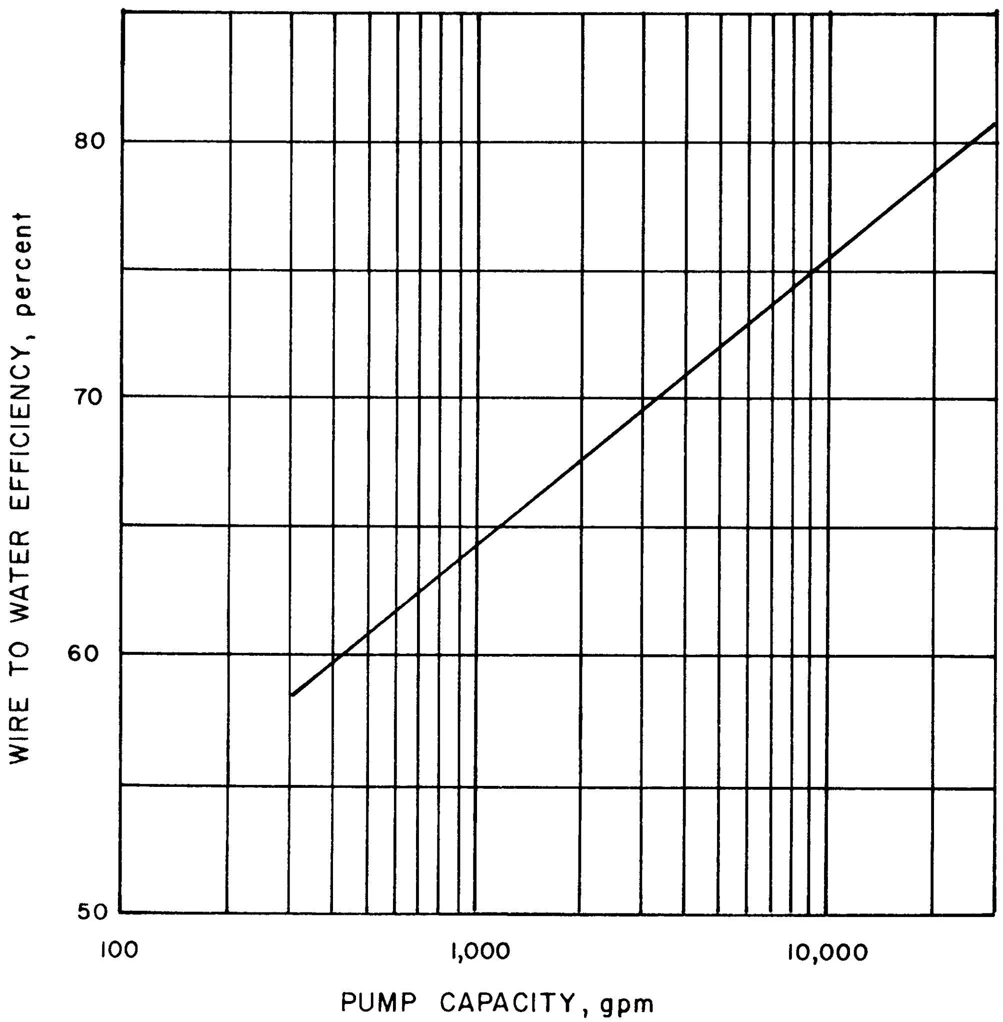


Figure 1. Hydraulic efficiency of centrifugal pumps.

TDH = 15 ft

therefore, $\text{kwh/day} = \frac{0.131 \times 24 \times Q \times 15}{E}$

$= \frac{47.1}{E}$ per mgd

and hp required $= \frac{2.63}{E}$ per mgd

- BW, backwash pumping

  T = 20 min per day per filter
  Q = 15 gpm per sq ft of filter area
  TDH = 25 ft

- SW, surface wash pumping

  T = 10 min per day per filter
  Q = 1 gpm per sq ft of filter area
  TDH = 200 ft

- WWR, wash water return pumping; pump to operate 24 hr per day and return all backwash and surface wash water to plant influent

  T = 24 hr per day
  Q = BW + SW volume per day
  TDH = 25 ft

- CF, chemical feed pumping

  2 feed pumps: 1 alum 1 polymer
  Q = 50 gal per hr each pump
  maximum dosage required: alum = 20 mg/l
  polymer = 0.8 mg/l

The energy required for filtration using these criteria, at 5 gpm per sq ft and a maximum filter area of 700 sq ft is shown in Figure 2. Energy requirements for a filtration rate of 5 gpm per sq ft and 2 gpm per sq ft are summarized in Table 1.

The energy estimates shown in Table 1 and Figure 2 are requirements using motor sizes that are commonly available. For example, calculated main stream pumping hp for a 5 mgd plant is about 18.8

$$\frac{2.63}{E} \times 5 = \frac{2.63}{0.70} \times 5 = 18.8 \text{ hp}$$

If a 20 hp motor is used, then 20 x 0.746 x 24 = 360 kwh required per day. Whereas using the relationship $\frac{47.1}{E}$ per mgd, gives 336 kwh required per day.

TABLE 1

FILTRATION ENERGY REQUIREMENTS

(kwh per day)

Plant Capacity mgd	P Main Stream Pump	BW Back Wash	SW Surface Wash	WWR Wash Water Return	CF Chemical Feed	TE Total Pressure	TE Total Gravity
						5 gpm/sq ft	
1	90	5	2	9	12	118	28
3	270	15	6	27	12	330	60
5	360	25	8	36	12	441	81
10	720	50	15	72	18	875	155
15	1075	75	23	90	18	1281	206
30	1800	150	45	179	36	2210	410
50	3600	250	75	270	72	4267	667
75	4500	375	113	405	108	5501	1001
100	6300	500	150	540	144	7634	1334
						2 gpm/sq ft	
1	90	13	5	18	12	138	48
5	360	63	19	90	12	544	184
10	720	125	38	135	18	1036	316
50	3600	625	188	720	72	5205	1605
100	6300	1250	375	1350	144	9419	3119

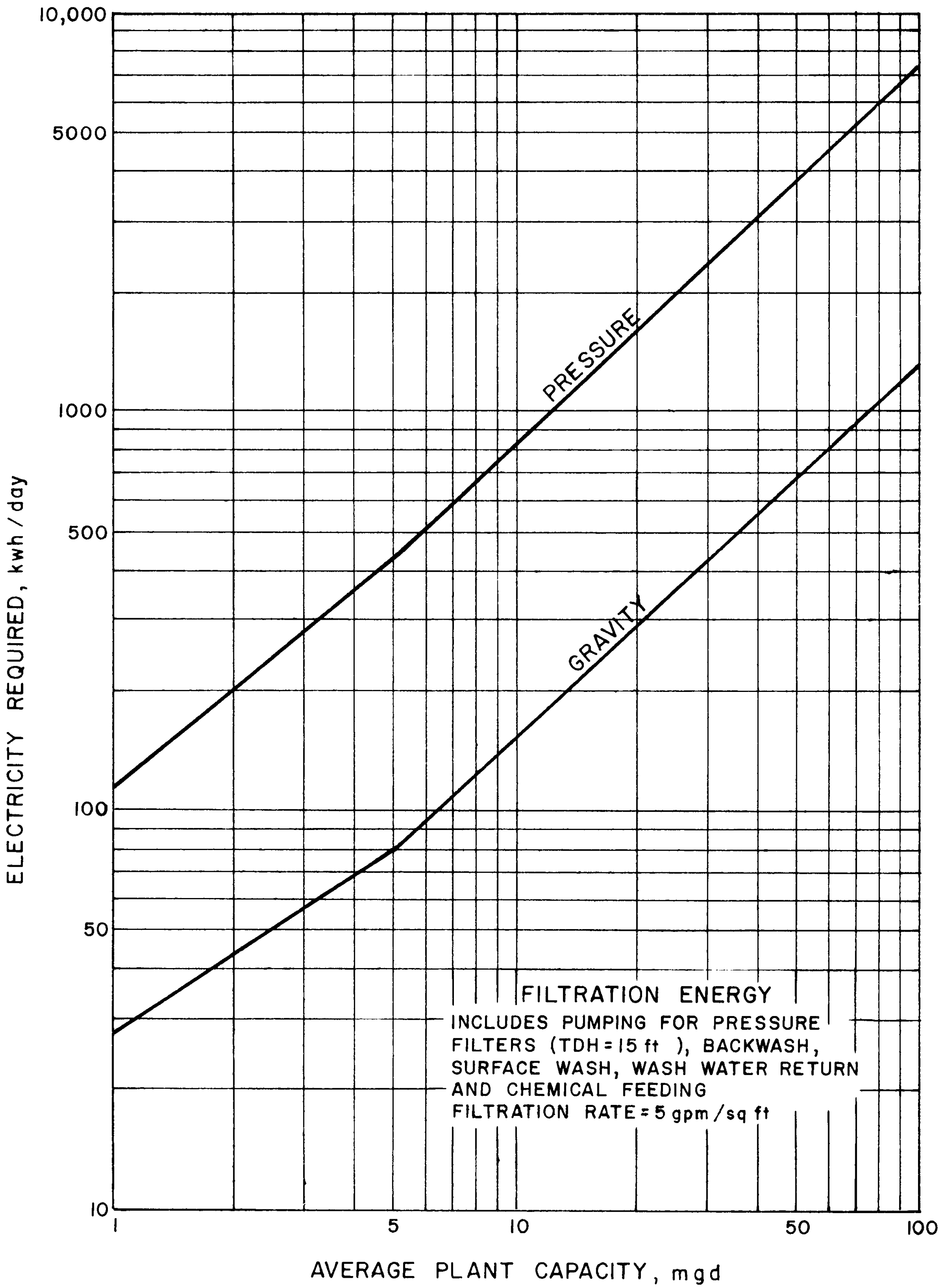


Figure 2. Energy required for pressure and gravity filtration.

The estimates in Table 1 indicate that energy for gravity filtration at a rate of 5 gpm per sq ft varies from about 0.028 kwh per 1000 gal in a 1 mgd plant to 0.013 kwh per 1000 gal in a 100 mgd plant. Energy for pressure filtration at a rate of 5 gpm per sq ft varies from about 0.12 kwh per 1000 gal in a 1 mgd plant to 0.08 kwh per 1000 gal in a 100 mgd plant. A lower filter rate of 2 gpm per sq ft requires more energy if it is assumed that the wash rate (15 gpm per sq ft for estimates in Table 1) remains constant.

These data show that main stream pumping consumes by far the greatest part of the energy required for filtration. The energy required for pumping is directly proportional to TDH; therefore, TDH in pressure filters (15 ft used in Table 1 and Figure 2) greatly influences the total energy required. Also, no energy for main stream pumping is assigned to gravity filtration in these estimates; however, energy is used (usually about 8 to 10 ft head loss at backwash) in gravity filters.

Equation (1) can also be used to calculate energy required for granular carbon adsorption by eliminating the term for chemical feeding. Also, TDH for carbon treatment in pressure contactors is higher than 15 ft in most installations because of the greater bed depths used.

Equation (1) may be used (in a computer program if desired) to calculate energy requirements for any set of flow, head and time conditions in gravity and pressure filters and carbon contactors. The program could also be written to use commonly available pump sizes for energy calculations.

SECTION 3

HEAT REQUIREMENTS

Estimates of heat requirements are presented for the following operations:

1. Building heat
2. Anaerobic digestion
3. Heat conditioning of sludge to improve dewatering
4. Wet oxidation of sludge
5. Lime recovery by recalcination
6. Granular carbon regeneration

BUILDING HEAT

Energy required for space heating in a wastewater treatment plant depends upon several factors including: (1) building size, (2) location (climate), and (3) type of construction. The degree-day (deg-day) system is one method of estimating energy required for space heating.

The deg-day is defined as 65^oF minus the mean temperature for the day. If the mean temperature of the day is 65^oF or greater, then the number of deg-days for heating is zero. The deg-day method is based on the findings of the American Gas Association that the quantity of energy required for heating is proportional to the number of deg-day. For example, a building requires twice as much heat on a day when the temperature is 45^oF (20 deg-day) than when the temperature is 55^oF (10 deg-day). Table 2 shows the average number of deg-day per month computed from about 30 years of record, for 25 cities in the United States.

The general equation used for estimating energy required for space heating is:

$$E = \frac{24 \times H \times D}{U}$$

E = energy consumption, Btu
U = utilization efficiency
H = hourly heat loss for building, $Btu/hr/^oF$
D = deg-day, ^oF day

The utilization efficiency is the ratio of the heat loss from the structure to the heat input and is a function of several factors including control of heating equipment and type of construction. Values from 45 to 90 percent have been reported. The hourly heat loss can be computed[5] or can be measured directly. It is expressed in $Btu/hr/^oF$ and includes the heat losses through the walls, ceiling, floor, windows and infiltration air. This quantity is highly variable from structure to structure depending on insulation, building materials and ratio of floor area to volume. Some representative heat loss values have been published for insulated and uninsulated walls and ceilings.[6] Based on these values, and neglecting air infiltration rate, H values were determined for the following three cases:

TABLE 2

AVERAGE MONTHLY DEGREE DAYS (HEATING) FOR VARIOUS CITIES

CITY	AVE WINTER TEMP	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	YEARLY TOTAL
Atlanta, Ga	51.7	0	0	18	124	417	648	636	518	428	147	25	0	2961
Baltimore, Md	46.2	0	0	27	189	486	806	859	762	629	288	65	0	4111
Birmingham, Ala	54.2	0	0	6	93	363	555	592	462	363	108	9	0	2551
Boston, Mass	40.0	0	9	60	316	603	983	1088	972	846	513	208	36	5634
Charlotte, N.C.	50.4	0	0	6	124	438	691	691	582	481	156	22	0	3191
Chicago, Ill	38.9	0	0	66	279	706	1051	1150	1000	868	489	226	48	5882
Cincinnati, Ohio	45.1	0	0	39	208	558	862	915	790	642	294	96	6	4410
Cleveland, Ohio	37.2	9	25	105	384	738	1088	1159	1047	918	552	260	66	6351
Dallas, Texas	55.3	0	0	0	62	321	524	601	440	319	90	6	0	2363
Denver, Colo	40.8	0	0	90	366	714	905	1004	851	800	492	254	48	5524
Detroit, Mich	37.2	0	0	87	360	738	1088	1181	1058	936	522	220	42	6232
Houston, Texas	62.0	0	0	0	0	165	288	363	258	174	30	0	0	1278
Kansas City, Mo	43.9	0	0	39	220	612	905	1032	818	682	294	109	0	4711
Los Angeles, Ca	60.3	0	0	6	31	132	229	310	230	202	123	68	18	1349
Miami, Fla	72.5	0	0	0	0	0	40	56	36	9	0	0	0	141
Milwaukee, Wis	32.6	43	47	174	471	876	1252	1376	1193	1054	642	372	135	7635
Minneapolis, Minn	28.3	22	31	189	505	1014	1454	1631	1380	1166	621	288	81	8382
New Orleans, La	61.8	0	0	0	12	165	291	344	241	177	24	0	0	1254
New York, N.Y.	42.8	0	0	30	233	540	902	986	885	760	408	118	9	4871
Philadelphia, Pa	44.5	0	0	30	205	513	856	924	823	691	351	93	0	4486
Pittsburgh, Pa	42.2	0	0	60	291	615	930	983	885	763	390	124	12	5053
St. Louis, Mo	44.8	0	0	36	202	576	884	977	801	651	270	87	0	4484
San Francisco, Ca	55.1	192	174	102	118	231	388	443	336	319	279	239	180	3001
Seattle, Wash	46.9	50	47	129	329	543	657	738	599	577	396	242	117	4424
Trenton, N.J.	42.4	0	0	57	264	576	924	989	885	753	399	121	12	4980

- Case A corresponds to an uninsulated building of 1000 sq ft with $H = 820$ Btu/hr/°F.

- Case B is a 1000 sq ft building with 3.5 in. wall insulation, 6 in. ceiling insulation and storm windows. The insulation and storm windows give a reduction of about 45 percent in the heat loss rate and $H = 450$ Btu/hr/°F.

- Case C is the same as Case B, but includes double glazed windows and floor insulation and gives $H = 325$ Btu/hr/°F.

These three cases are shown in Figure 3 as a function of the number of deg-day and a U of 0.70. Infiltration air can substantially increase these values. For example, an infiltration rate of 1.5 times the building volume per hour will increase the values for Cases A, B and C by 13, 24 and 33 percent, respectively.

In wastewater treatment plants, 4 to 6 air changes per hour is a common design standard[7]. This rate will increase the heating requirement and should not be neglected. For example, assuming 4 air changes/hr, 70 percent utilization factor, 5000 deg-day climate, and 1000 sq ft floor area with an 8 ft ceiling gives an additional heat requirement of about 99 million Btu/yr.

Building heating requirements for wastewater treatment plants can be estimated from the above information if the total floor area is known. Typical floor areas as a function of treatment plant size are given in the EPA report by Smith[4] and are shown in Figure 4. The data in these tables and figures can be used to estimate building heating requirements. As an example, the curves shown in Figure 5 were derived from these data for Los Angeles, New York and Minneapolis.

ANAEROBIC DIGESTION HEAT REQUIREMENTS

Heat is required in the anaerobic digestion process to (1) raise the temperature of the influent sludge to the level of the digester, and (2) compensate for heat losses from the digester through its walls, bottom and cover. The optimum temperature for sludge digestion in the mesophilic range is about 95°F. The heat required to raise the influent sludge temperature can be calculated from the following relationship:

$$Q = WC\,(T_D - T_S) \qquad (5)$$

where

Q = heat required, Btu
W = weight of influent sludge, lb
C = specific heat of sludge, 1.0 Btu/lb/°F for 1 to 10% solids sludge
T_D = temperature in digester, °F
T_S = temperature of influent sludge, °F

The WPCF Manual of Practice No. 8, gives the following criteria for digester heating:[8]

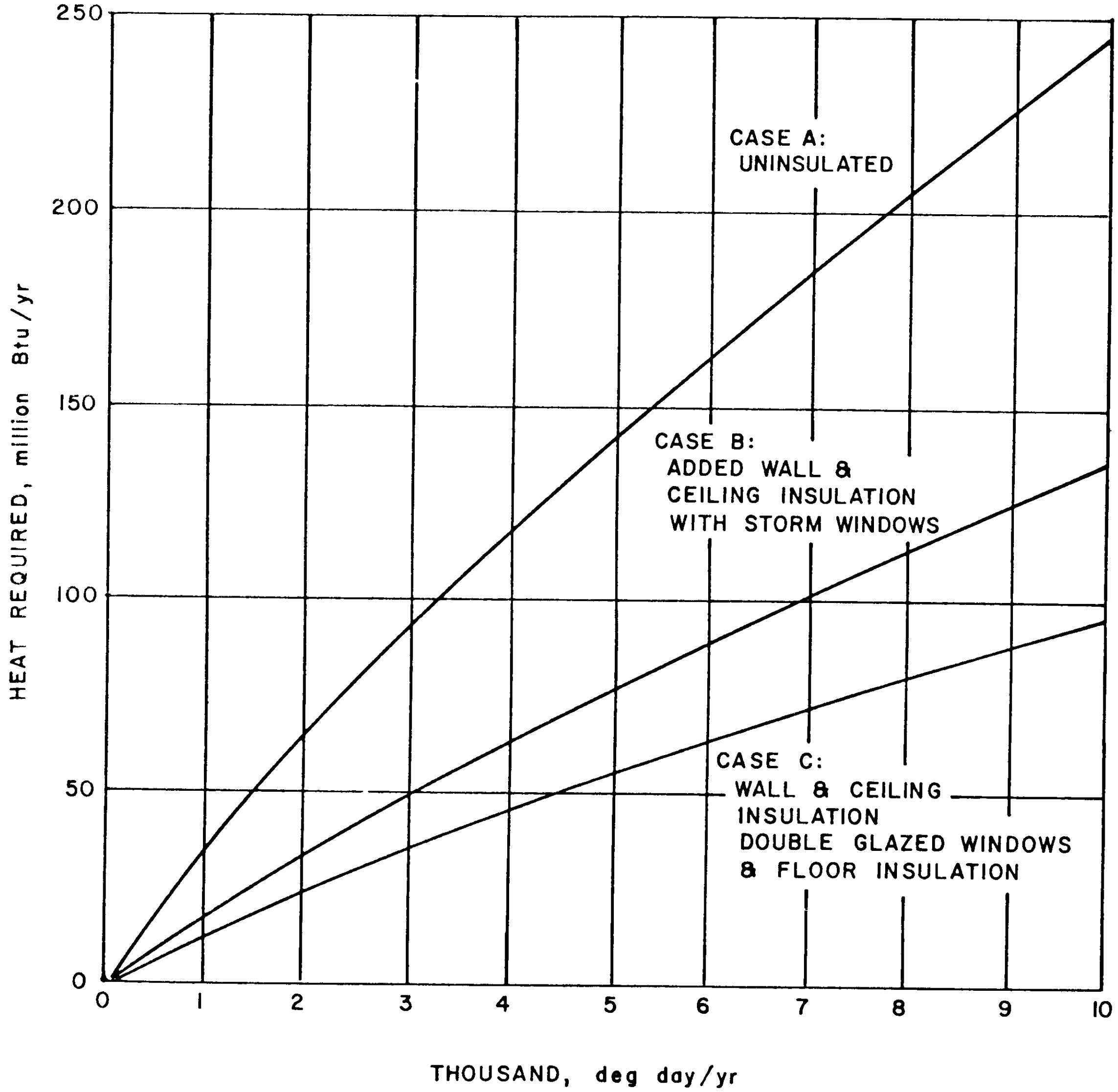


Figure 3. Heat required for 1,000 sq ft building.

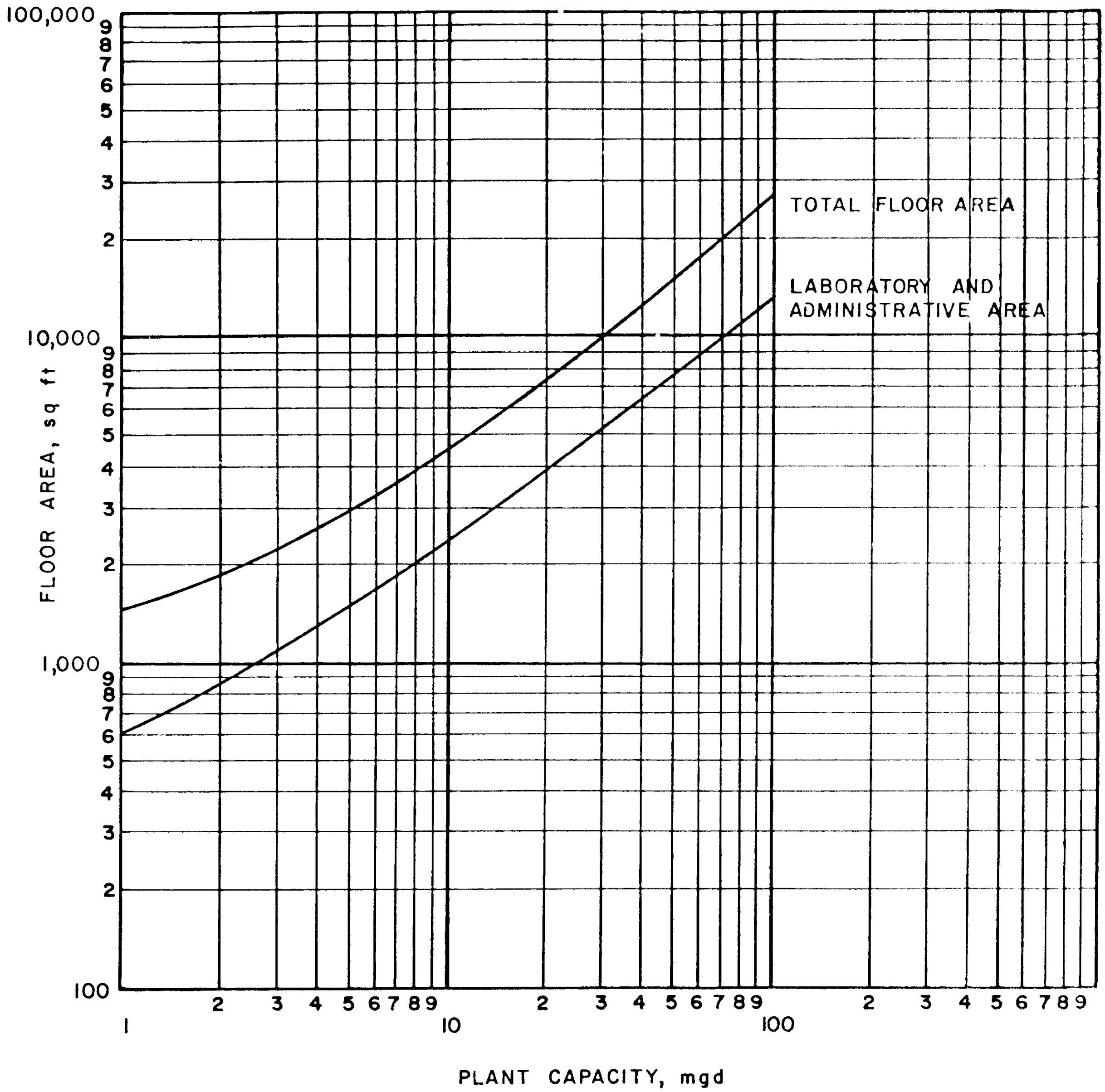
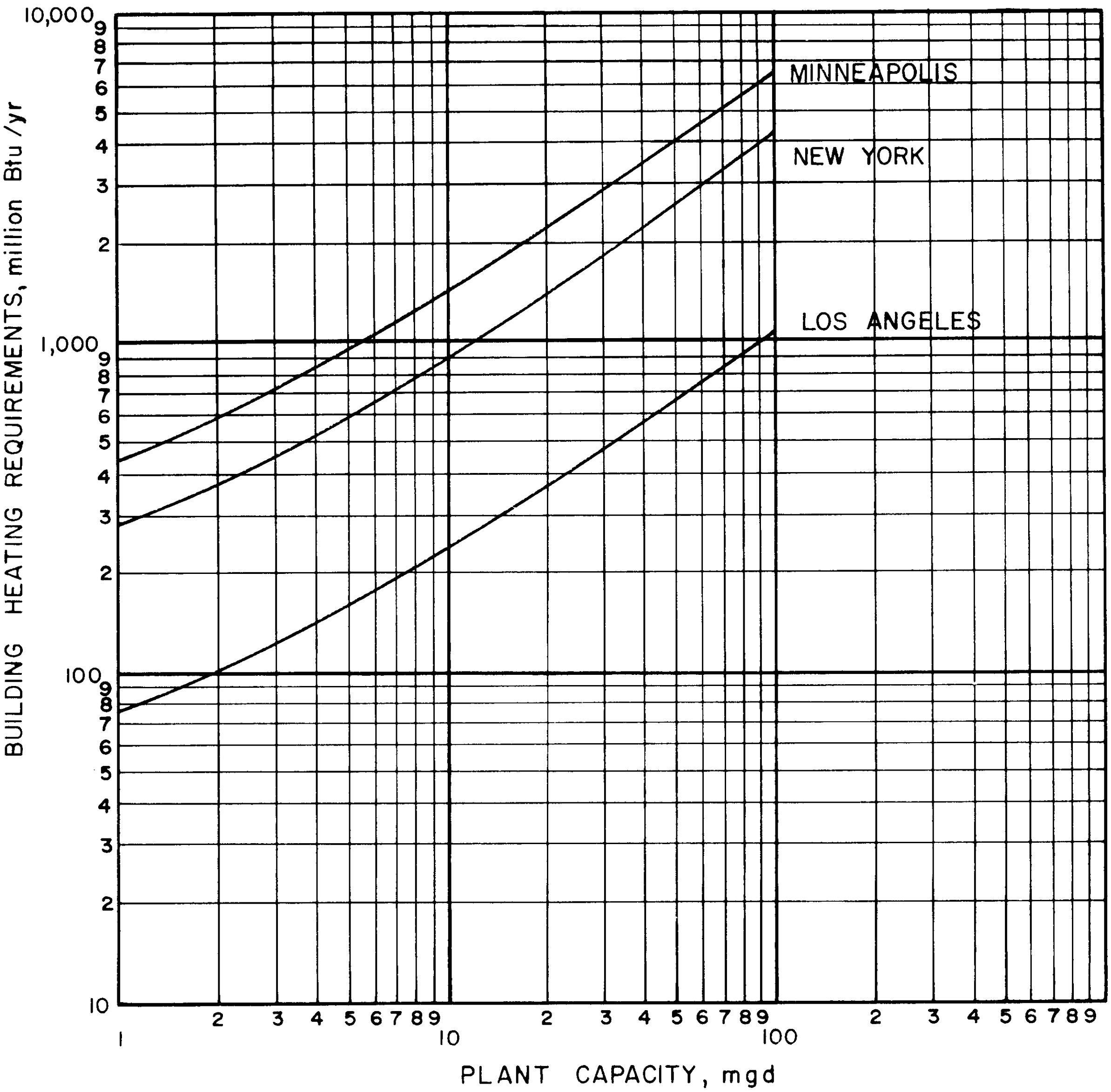


Figure 4. Floor area required in wastewater treatment plants.



DESIGN ASSUMPTIONS:
FOUR FRESH AIR CHANGES/hr
STORM WINDOWS & INSULATED WALLS & CEILINGS
70 PERCENT FUEL UTILIZATION FACTOR

Figure 5. Building heating required in wastewater treatment plants.

Data accumulated from numerous digester installations have made it convenient to use factors for estimation of heat losses from digesters without considering separately the loss through each element of the digester. For the normal installation it is assumed that a 1°F drop in temperature occurs for the entire tank contents in 24 hrs. A correction factor is applied for outside temperature, depending upon location and special conditions, such as the presence of ground water. For each 1,000 cu ft of contents, this amounts then to 1,000 x 62.5 x 1.0 = 62,500 Btu per day; or $\frac{62,500}{24}$ *= 2,600 Btu per hr. Correction factors for geographical location by which the value of 2,600 Btu per hr is multiplied are as follows:*

Northern United States	*1.0*
Middle United States	*0.5*
Southern United States	*0.3*

The WPCF Manual of Practice No. 11[9] gives the following loadings for anaerobic digesters:

	Loading, lb VS/day/cu ft
Standard Rate	0.03 to 0.1
High Rate	0.1 to 0.4

Digester heat requirements for this paper are based on loadings of 0.05 and 0.15 lb VS/day/cu ft. These criteria give the following digester capacities:

Sludge Type	Solids Content (percent)	Total Solids (lb/mil gal)	Volatile Solids (lb/mil gal)	Total Sludge (lb/mil gal)	Digester Capacity (cu ft/mil gal) Loading (lb VS/day/cu ft) 0.05	0.15
Primary	5	1155	690	23,100	13,800	4,600
Primary Plus WAS	4.5 (thickened)	2100	1446	46,600	28,900	9,600

The total heat required for digestion at 95°F at the two loadings is shown in Figure 6 for primary plus waste activated sludge. These heat requirements are based on the above criteria for sludge heating and digester heat loss and a 75 percent heat transfer efficiency.

HEAT TREATMENT OF SLUDGE

Heat treatment comprises several related processes in which sludges are heated for conditioning prior to dewatering or for stabilization prior to disposal. All the processes involve heating sludge for relatively short periods of time in pressurized reactors. The reactor's environment - temperature, pressure, residence time and oxygen content - is selected based on the desired degree of sludge conditioning or stabilization. As the

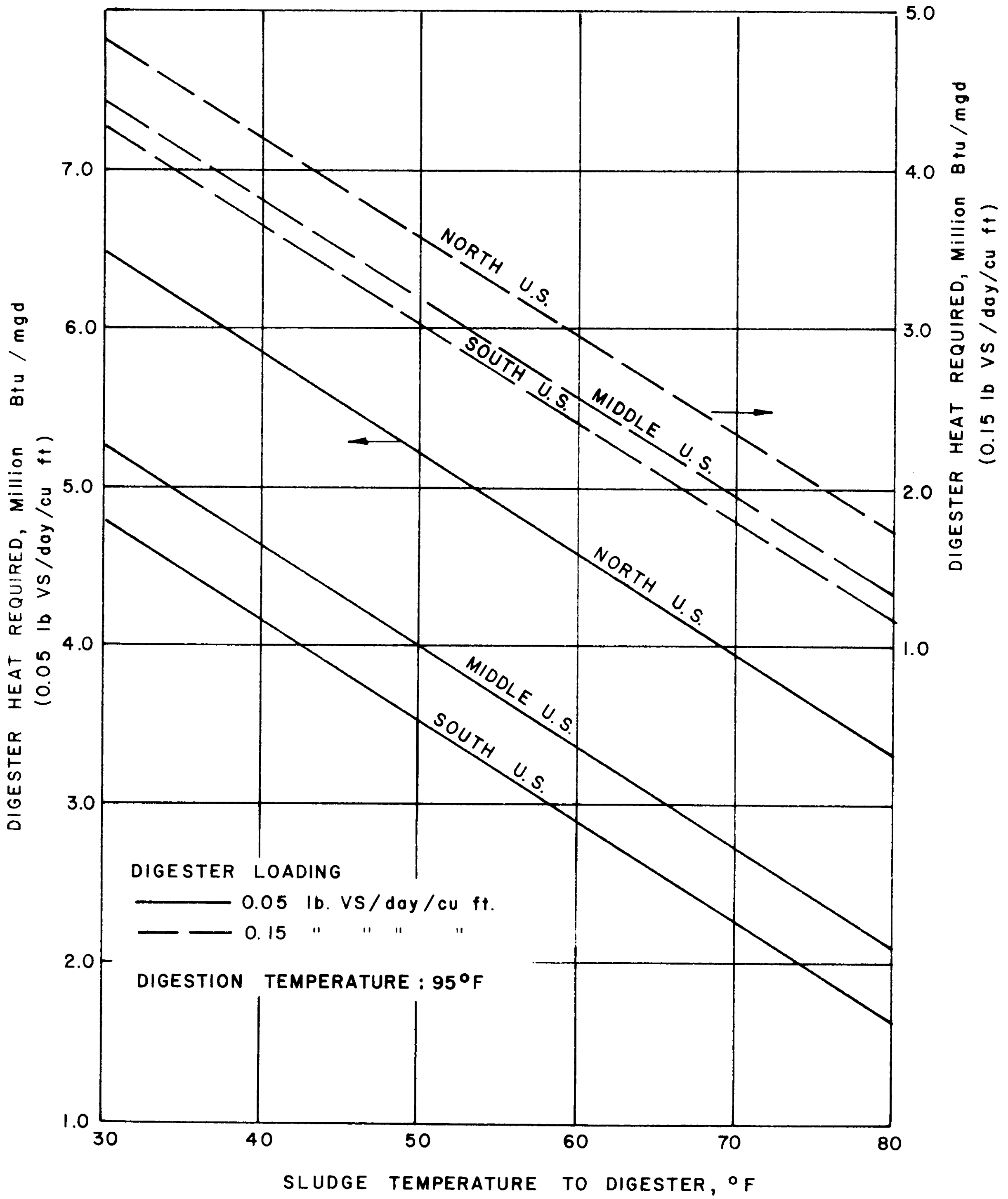


Figure 6. Anaerobic digester heat required for primary plus waste activated sludge.

temperature and amount of available oxygen are increased a greater amount of stabilization or oxidation takes place. Heat treatment processes are divided into two main categories depending on the desired results: thermal conditioning and wet oxidation.

Thermal Conditioning

Thermal conditioning is used to condition sludge for subsequent dewatering. Under heat and pressure in a reactor, bound water and intercellular water are released from the sludge and much of the smaller and more hydrated particulate matter is solubilized. The result is a mixture of relatively innocuous, sterile particulate matter and a liquid. The two phases are easily separated after discharge by decantation and mechanical dewatering processes. The dewatered solids are inoffensive and can be used as soil conditioner. The liquid phase is highly colored, often has a very offensive odor and has a BOD ranging between 3,000 and 15,000 mg/l.

For thermal conditioning of most municipal sludges, reactor temperatures and pressures range between 300 and 500°F and 200 and 400 psi. Residence time in the reactor is usually about 30 to 45 minutes at design flow. A primary purpose in pressurizing the reactor is to prevent the liquid contents from flashing to steam at the high temperatures involved. Air may be added to the system to assist with heat transfer and to partially oxidize the sludge.

Wet Oxidation

This process oxidizes organic materials in the sludge to ash. Wet oxidation is similar to thermal conditioning in that sludge is heated in a pressurized reactor, but it's purpose is to stabilize the sludge rather than condition it for dewatering. This requires an increase in reactor temperatures to a range between 450 and 700°F and pressures to between 750 psi and 1800 psi. The reactor's environment is selected based on the characteristics of the sludge and the degree of oxidation desired. Air is added to the reactor to supply the oxygen needed by the chemical reactions taking place. The degree of oxidation of the sludge can be controlled and can range up to over 95 percent of the influent COD for some sludges. This is equivalent to results attainable in dry incineration processes, but in wet oxidation, temperatures are much lower, fly ash is not a problem and the sludge need not be dewatered before being oxidized.

Heating Requirements

In order to operate any heat treatment process, the temperature of the incoming sludge must be raised to the selected reactor temperature. To heat one gallon of sludge from 50°F to a thermal conditioning temperature of 350°F requires 2500 Btu and to raise the temperature to 700°F for complete oxidation requires about 5500 Btu. Thus a 10 mgd treatment plant producing 10 tons per day of sludge requires approximately 150 mil Btu/day for thermal conditioning and 320 mil Btu/day for wet oxidation. These values are net heats required by the sludge and must be increased to reflect the efficiency of the heat generating and transferring system and losses from the overall system. The actual energy input is, therefore, almost double the above figures.

Heat exchangers are incorporated into the processes to capture the heat from the treated sludge in the reactor outlet. In this manner, incoming sludge is heated to within 40 to 50°F of the reactor temperature with a corresponding drop in required input energy. With an efficient heat exchange system, about 420 Btu/gal is required to reach the reactor temperature and, accounting for system inefficiencies, a total energy input of about 900 Btu/gal is required. This heat is normally supplied by injecting steam into the reactor.

Heat to generate the steam is usually produced in gas or oil-fired boilers. However, when sludge incinerators follow thermal conditioning plants, waste heat boilers deriving heat from the incinerator stack gases have been used successfully to provide all the required heat.

Injection of air into the reactor allows heat-producing oxidation reactions to occur. In those thermal conditioning systems where air is supplied, oxidation of about 5 to 10 percent of the volatile solids takes place. Assuming typical wastewater sludges and a heat value of 10,000 Btu/lb of volatile solids, the required heat input is reduced from 900 Btu/gal to between 500 and 700 Btu/gal. This reduction in required heat is accompanied, however, by an increase in electrical energy needed to compress the air. Table 3 shows the heat input required for thermal conditioning of several sludges and Figure 7 shows the annual heat requirements for various sludges.

By increasing the degree of oxidation, as is done in wet oxidation, to 20 to 30 percent of the volatile solids content, enough heat is produced in the reactor to offset the need for supplementary steam. Steam is then needed only to initially heat the system to the reaction temperature. Further increase in the degree of oxidation produces excess heat which may be used to generate steam or hot water for other uses. Or, hot, pressurized off-gases from the reactor can be expanded through a turbine to drive process equipment or an electrical generator.

The recoverable energy from a wet oxidation system treating the primary and waste activated sludge mixture described in Table 3 can yield almost 16 horsepower per gpm of capacity. Comparing this recoverable energy with the energy required to operate the system shows that the output very nearly equals input. Of course, the energy balance will change for different sludges amd system conditions, but in all systems a large amount of the input energy is recoverable.

Sidestreams

Besides the direct energy requirements of heat treatment, other related areas of energy use must be considered. These are the treatment of the high-strength liquors produced in the reactor and the treatment of odorous gases emanating from air-water separators, storage tanks, and subsequent

TABLE 3

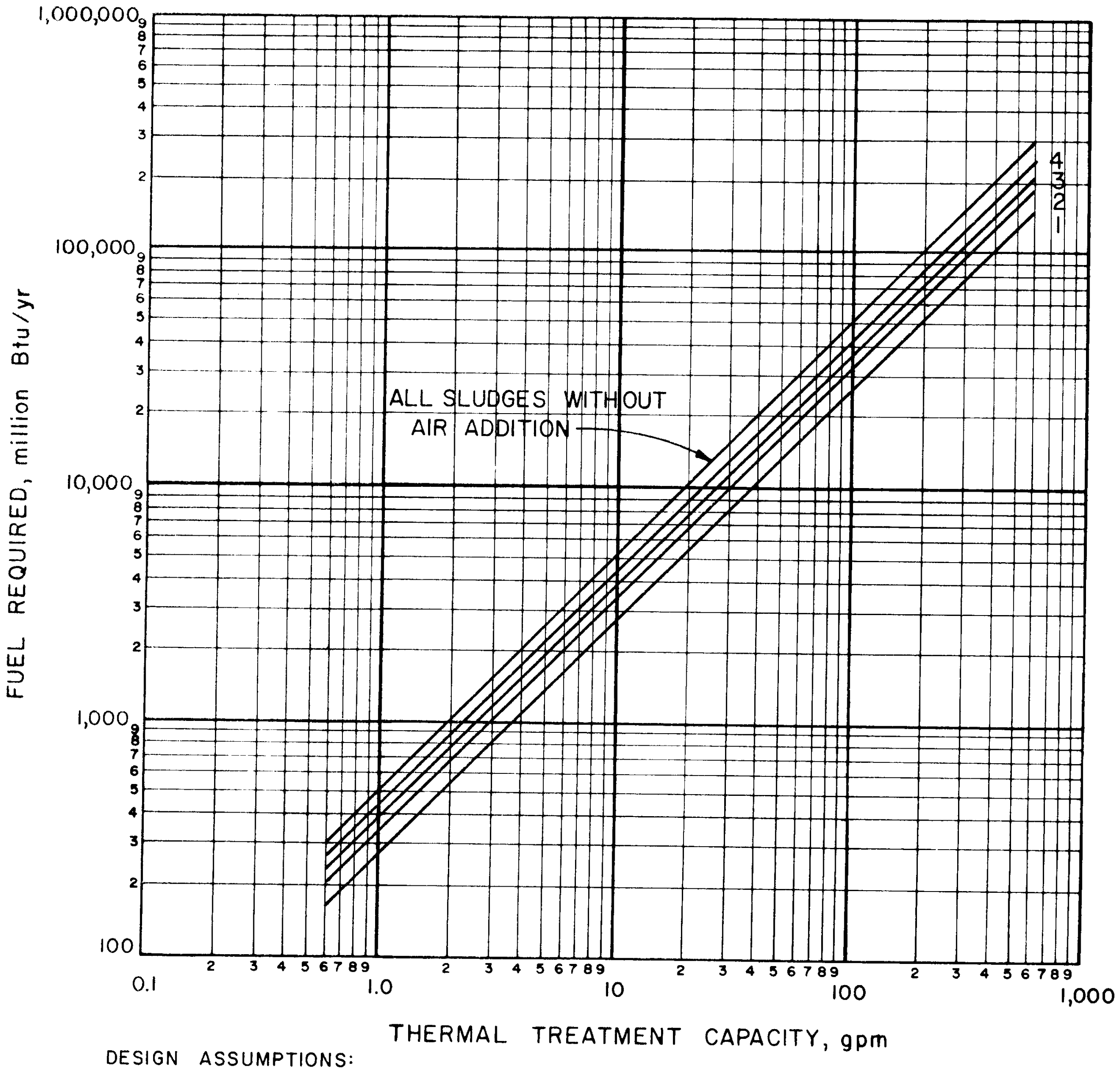
FUEL REQUIREMENTS FOR THERMAL TREATMENT WITH AIR ADDITION

Sludge[1]	Sludge Quantity lb/mil gal	Solids Concentration to Reactor %	Volatile Solids %	Heat Value of Sludge[2] Btu/gal	Heat Liberated[3] Btu/gal	Fuel Input Required[4] Btu/gal
P	1151	5	60	2502	155	564
P + WAS	2096	4.5	69	2590	165	542
P + WAS(+$FeCl_3$)	2685	3.5	54	1576	95	693
P(+$FeCl_3$)+WAS	3144	3	53	1326	80	726
WAS	945	2.5	80	1668	110	661
WAS(+$FeCl_3$)	1535	3	50	1251	80	726
Dig P	806	6	43	2152	135	607
Dig P + WAS	1226	4	47	1578	95	693
Dig P+WAS(+$FeCl_3$)	1817	4	33	1100	65	758
Tert Alum	700	2	30	500	35	822

[1]Abbreviations:

P = Primary Sludge
WAS = Waste Activated Sludge
Dig = Digested
Tert = Tertiary
$FeCl_3$ = Ferric Chloride

[2]Based on 10,000 Btu/lb VS
[3]Based on 5 - 10% oxidation of VS
[4]Based on 62% overall system efficiency



DESIGN ASSUMPTIONS:

REACTOR CONDITIONS – 300 psig at 350°F
HEAT EXCHANGER $\Delta T = 50°F$
CONTINUOUS OPERATION
SEE TABLE 3 FOR SLUDGE DESCRIPTION

CURVE INCLUDES:

FUEL TO PRODUCE STEAM NECESSARY TO RAISE REACTOR CONTENTS TO OPERATING TEMPERATURE

CURVE No.	SLUDGE TYPE WITH AIR ADDITION
1	PRIMARY + WAS
2	WAS
3	PRIMARY (+$FeCl_3$)+WAS & PRIMARY+WAS (+$FeCl_3$)
4	TERTIARY ALUM

Figure 7. Fuel required for heat treatment of sludge.

dewatering processes. Often, costs and energy requirements for these operations are incorrectly excluded when making feasibility studies involving the processes. Their impacts on energy consumption can be substantial.

Strong liquors from thermal conditioning processes which include supernatant from decanting operations and filtrate or centrate from dewatering operations, must be treated before discharge. These liquors are usually treated in one of three ways: (1) separate biological treatment (aerobic or anaerobic) perhaps followed by adsorption on activated carbon, (2) recycled directly back to the primary or secondary treatment plant, or (3) biological pretreatment and then recycled back to the main treatment plant for additional treatment. Because of its high-strength (BOD of 3,000 to 15,000 mg/l and suspended solids of 10,000 to 20,000 mg/l) and even though the volume is low (0.4 to 0.8 percent of the inflow to the treatment plant), the increased load due to recycling or separately treating can be quite significant. Recycling strong liquor directly to an activated sludge plant can increase the air requirements, and consequently the energy requirement, by as much as 30 percent.

Most of the various systems available to control concentrated process odors also consume relatively large amounts of energy. The methods most commonly used and most generally effective for controlling odors from thermal treatment are high temperature incineration, adsorption on activated carbon, and chemical scrubbing. Table 4 shows the requirements for the three methods based on a typical 1,000 cfm odor control system. A concentrated gas stream of 1,000 cfm corresponds to a thermal treatment plant size of 200 to 250 gpm or a sewage treatment plant size of 50 to 60 mgd. The energy requirements developed for the three methods represent the needs of complete odor control systems and include requirements for collection of gases; ducting; fans; chemical feeding, mixing, and storage equipment; automatic control systems; disposal of removed and waste materials; and discharge of treated gases as well as for odor removal itself.

The incineration or afterburning process considered consists of pretreatment by water scrubbing using treated effluent in a packed bed and direct-flame incineration of 1,500^{o}F with recovery of 40 percent of the input heat. The carbon adsorption process includes prescrubbing with effluent, dual-bed adsorption on activated carbon, regeneration of carbon with low pressure steam, condensation of vapors, and incineration of the waste organic stream. The chemical scrubbing system utilizes three stages of scrubbing in packed beds. The first two stages use secondary effluent and a final stage uses a buffered, potassium permanganate solution.

HEAT REQUIRED FOR LIME RECOVERY BY RECALCINATION

Wastewater treated with lime produces sludge composed of varying amounts of relatively inert and non-combustible material, such as calcium carbonate, $CaCO_3$, magnesium hydroxide, $Mg(OH)_2$, phosphorus precipitates and others. The sludges also contain combustible organic material with with some heat value. Lime as calcium oxide, CaO, is recovered in the recalcining process according to the following relationship:

TABLE 4

ENERGY CONSUMPTION FOR ODOR CONTROL SYSTEMS

	Incineration	Carbon Adsorption	Chemical Scrubbing
Electrical Energy			
kwh/1000 cu ft	122	146	146
kwh/yr (1 mgd)[2]	1285	1540	1540
kwh/yr (1 gpm)[3]	321	385	385
Fuel[1]			
million Btu/1000 cu ft	36.8	1	---
million Btu/yr (1 mgd)[2]	387	11	---
million Btu/yr (1 gpm)[3]	97	2.7	---

[1]Based on continuous operation

[2]1 mgd indicates approximate sewage treatment plant capacity

[3]1 gpm represents approximate thermal treatment plant capacity

$$CaCO_3 + heat \rightarrow CaO_2 + CO \text{ (gas)}$$

Fuel requirements for several different types of lime sludges are shown in Figure 8. The sludge characteristics are given in Table 5. These fuel requirements are based on the experience of furnace manufacturers.

- Case A illustrates a typical sludge resulting from lime addition to raw sewage where no lime recycle is practiced. In this instance, the multiple hearth furnace is actually being used for incineration and disposal rather than recalcining.
- Case B is based on a system where raw sewage is lime coagulated and the lime is recovered and recycled.
- Case C illustrates a tertiary lime coagulation system where the sludge is not classified prior to recalcination.
- Cases D, E, and F illustrate tertiary systems where classification is practiced with varying sludge moisture content entering the furnace. The heating value of natural gas is taken as 1,000 Btu per cu ft.

HEAT REQUIRED FOR GRANULAR CARBON REGENERATION

Granular activated carbon is reactivated in multiple hearth furnaces fueled by natural gas or other fossil fuels. Steam is also commonly used in the reactivation process. Relatively small amounts of electricity are required for furnace operation and for carbon transfer.

Operating data reported at South Lake Tahoe[10] indicate the following energy requirements for on-site regeneration of activated carbon:

	Btu per lb Carbon Reactivated
Electricity	700
Natural Gas (furnace)	3,600
TOTAL	4,300

Energy to supply steam and to operate an afterburner is not included in the total of 4,300 Btu per lb.

A paper written by employees of a carbon manufacturer[11] gives the following requirements for reactivation of granular carbon:

TABLE 5

FEED CHARACTERISTICS FOR LIME RECALCINING FUEL REQUIREMENTS

	CASE A	CASE B	CASE C	CASE D	CASE E	CASE F
Moisture Content	60%	60%	50%	50%	55%	60%
Solids Analysis:						
$CaCO_3$	38%	65%	71%	86.1%	86.1%	86.1%
$Mg(OH)_2$	0%	2%	10%	4.3%	4.3%	4.3%
Other Inert	24%	13%	16%	6.1%	6.1%	6.1%
Combustibles	38%	20%	3%	3.5%	3.5%	3.5%
Calciner Operation:						
Gas Outlet Temperature	800^0F	900^0F	900^0F	900^0F	900^0F	900^0F
Product Outlet Temperature	600^0F	1400^0F	1400^0F	1400^0F	1400^0F	1400^0F

Case

A Lime addition to raw sewage, no classification, no recycle (incineration for disposal)

B Lime addition to raw sewage, centrifugal classification, recycle

C Tertiary lime sludge, no classification, recycle

D,E,F Tertiary lime sludges, centrifugal classification, recycle

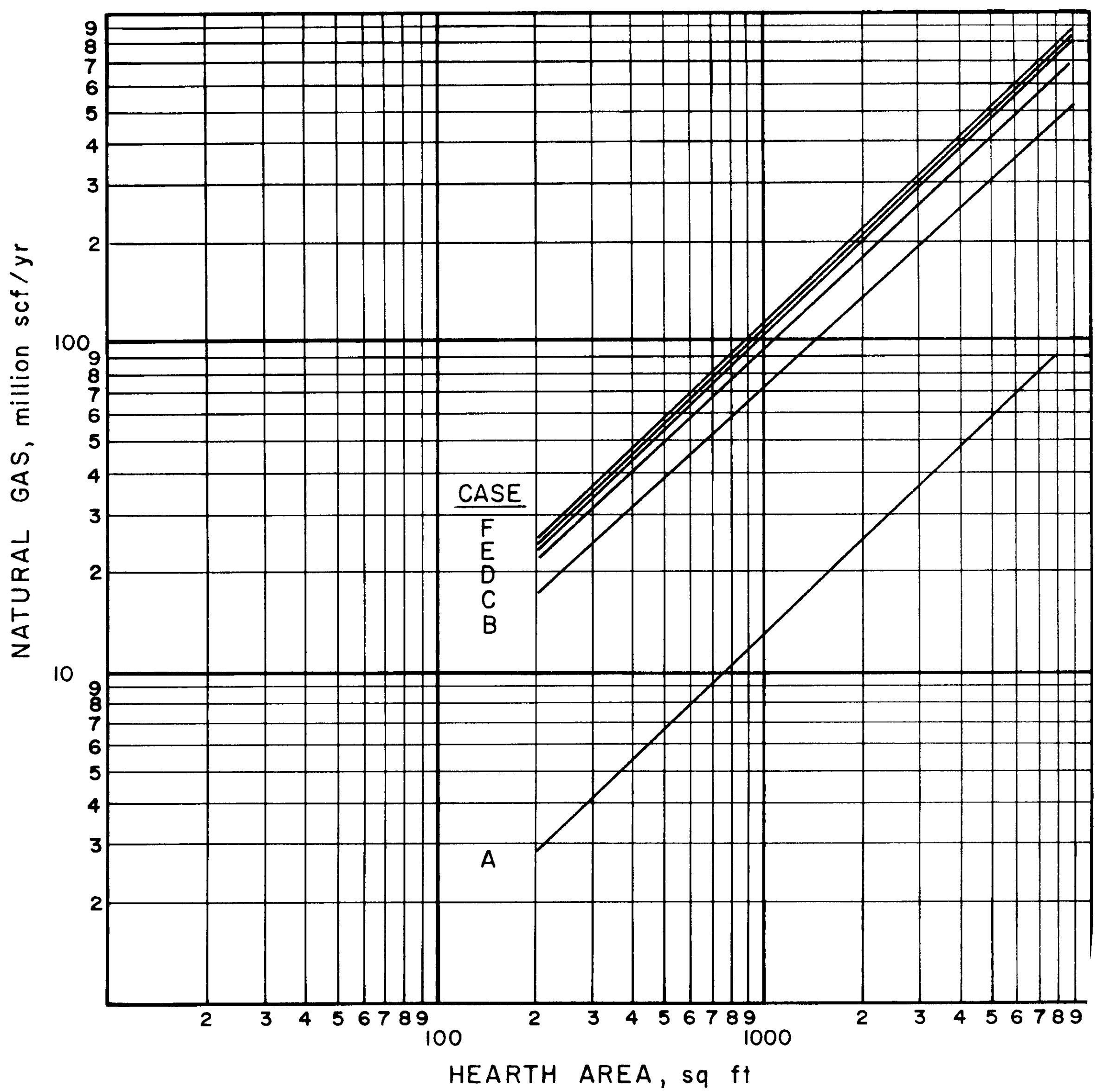


Figure 8. Natural gas required for lime recalcining (See Table 5 for sludge characteristics).

		Btu per lb Carbon Reactivated
Reactivation		2,180
Afterburner		2,080
	TOTAL	4,260

The maximum total energy required for on-site reactivation of granular carbon is considered to be about 8,300 Btu per lb including requirements for air pollution control equipment.

		Btu per lb Carbon Reactivated
Electricity		700
Furnace fuel		3,600
Steam		1,600
Afterburner		2,400
	TOTAL	8,300

SECTION 4

UTILIZATION OF ANAEROBIC DIGESTER GAS

The purposes of this section include the following:

1. Estimate the total cost for cleaning and storing digester gas as a function of the amount of storage and the amount of gas processed.

2. Estimate the electrical energy available as a function of gas consumption.

3. Estimate waste heat available from exhaust gas and water jackets of internal combustion (IC) engines large enough to make a practical system.

4. Estimate the cost of an installation for generating electrical power from digester gas as a function of the kilowatt capacity of the installation. Alternate fuel, either natural gas or fuel oil must be provided when the supply of digester gas is inadequate. Include waste heat recovery where size makes this practical.

5. Estimate the cost and horsepower of direct coupled IC engines for driving influent pumps or air blowers as a function of gas consumption.

6. All costs to be broken down into construction cost, operating and maintenance labor, materials and supplies and energy similar to the Black and Veatch report.[12]

EXISTTNG TREATMENT FACILITIES

Information was obtained from the following agencies that utilize sludge digester gas:

Atlanta, Georgia
Bloom Township, Illinois
Buffalo, New York
Cincinnati, Ohio
Cleveland, Ohio
Fort Worth, Texas
Los Angeles, California (City)
Los Angeles County Sanitation District
Orange County Sanitation District (California)
Philadelphia, Pennsylvania
San Jose, California
Tucson, Arizona

Madison, Wisconsin and Racine, Wisconsin are also using some digester gas but no data was obtained from these cities. Following is a summary of the information that was obtained.

Atlanta, Georgia

A 90 mgd treatment plant was recently completed and no data is available on the quantity or details of utilization of digester gas. The plant is equipped with three dual fuel engines which are designed to drive blowers.

Bloom Township, Illinois

Digester gas is not now used in internal combustion engines in this plant because of high maintenance costs. From May 1973 through April 1974, an average of about 58,000 cu ft/day of gas was produced and about 3.5 cu ft was produced per lb of VS added to the digester.

Buffalo, New York

Internal combustion engines are not used at this plant. Sludge digester gas is used as fuel for: two boilers to heat digesters; an incinerator which burns sludge cake; and building heat. There are no gas cleaning or storage facilities. Accurate records of gas production are not available.

Cincinnati, Ohio

Digester gas is utilized at the Mill Creek Treatment Works in four 1910 hp turbo-charged dual fuel engines to drive four 1350 kw generators. Heat recovery units are used to furnish steam for heating the digesters. Data from 1973-75 are summarized in Table 6 and show that an average of 17.8 scf of digester gas was required to produce one kwh of electricity. Data from other plants in Cincinnati indicate that digester gas produced ranged from 10.9 to 13.4 cu ft per lb of VS destroyed.

Cleveland, Ohio

The sludge digester gas system will be removed from this plant in the near future in connection with the expansion and installation of a different solids handling system. Digester gas is not used for engine fuel but is used to heat the digesters and as fuel for a sludge incinerator. Digester gas is produced at the rate of about 500,000 cu ft per day and about 5 cu ft per lb of VS destroyed.

Fort Worth, Texas

The following information is based on the period October 1, 1973 through September 30, 1974.

TABLE 6
ELECTRICITY GENERATED AT CINCINNATI
MILL CREEK TREATMENT WORKS

	Month	(1) Oil Used (gallons)	(2) Oil Generated (kwh)	(3) Total Gen. (kwh)	(4) Gas Gen. (kwh)	(5) Gas Used (scf)	(6) scf Gas Used / kwh Generated
1973	July	26,030	348,800	1,826,300	1,477,500	25,525,800	17.3
	Aug.	133,655	1,791,000	1,825,000	34,000	1,879,200	55.3*
	Oct.	61,366	822,300	1,859,125	1,036,800	16,324,920	15.8
	Nov.	16,183	216,900	1,805,000	1,588,100	24,864,480	15.7
	Dec.	78,966	1,058,100	1,765,700	707,600	10,970,640	15.5
1974	Jan.	99,729	1,336,400	1,666,900	330,500	5,104,800	15.4
	Feb.	102,073	1,367,800	1,588,000	220,200	3,524,400	16.0
	Mar.	105,485	1,413,500	1,835,500	422,000	6,753,960	16.0
	Apr.	72,841	976,100	1,645,400	669,300	10,643,760	15.9
	May	62,802	841,500	1,733,900	892,400	15,357,240	17.2
	June	45,986	616,200	1,686,500	1,070,300	17,960,040	16.8
	July	106,349	1,425,100	1,706,600	281,500	5,359,000	19.0
	Sept.	104,038	1,394,100	1,684,000	289,900	6,519,600	22.5
	Oct.	81,555	1,092,800	1,754,400	661,600	12,318,480	18.6
	Nov.	37,763	506,000	1,861,000	1,355,000	25,261,560	18.6
	Dec.	62,374	835,800	1,930,100	1,094,300	19,532,880	17.9
1975	Jan.	93,314	1,250,400	1,952,800	702,400	15,048,360	21.4
	Feb.	79,395	1,063,900	1,596,000	532,100	9,762,120	18.6
	Mar.	116,552	1,561,800	1,893,900	332,100	6,998,400	21.1
	Apr.	102,611	1,375,000	1,784,500	409,500	7,739,640	18.9
	May	90,310	1,210,200	1,851,125	641,000	12,072,600	18.8
	June	64,538	864,809	1,688,125	823,300	14,133,240	17.2

Range 15.4 - 22.5
Ave. 17.8

Column (2) = Column (1) x 13.4
Column (4) = Column (3) - Column (2)
Column (6) = Column (5) ÷ Column (4)

* Not included in the range and average

Average flow treated	38.8 mgd
Average VS destroyed in digesters	47 percent
Gas produced	4.2 scf/lb of VS destroyed
Average power generated	19.7 scf digester gas required to generate 1 kwh electricity

Two 1620 hp White Superior dual fuel engine generator sets were installed in June 1972. The generators are rated at 1180 kw each. One 1440 hp gas engine is used to drive one blower. The engines are equipped with heat recovery units which are used to heat the digesters. Gas is compressed and stored at 35 to 45 psi in a 50 ft diam sphere (65,000 cu ft capacity). An iron sponge type scrubbing system was installed with the engines but is not used because the hydrogen sulfide concentration is less than 1,000 ppm. The large White Superior engines are turbo-charged and gas must be supplied at a minimum pressure of 35 psi.

Los Angeles, California

The Hyperion Plant treats an average flow of 340 mgd all of which receives primary treatment and 100 mgd receives conventional activated sludge treatment. Sludge treated in the digesters is about 92 percent primary and 8 percent waste activated. There are 18 digesters, 15 operate at 95°F and three at 122°F. Following is a summary of engine operation and gas production data during the last three fiscal years:

	1971-72	1972-73	1973-74
Gas Production			
million cu ft per day	4.186	3.843	3.548
Heat Value*, Btu/cu ft	590	590	590
cu ft gas produced/lb VS destroyed	17.7	13.4	11.7
Engine Operation			
Btu/hp-hr	6,469	6,428	7,675
Electricity Generated			
kwh/day	58,533	59,349	56,847

*Lower heating value from laboratory tests

Engineers at the Hyperion Treatment Plant believe that the reduction in gas production indicated in the last two years is the result of poor metering and does not represent a change in actual gas production. The gas is compressed to 35 psi and stored. The hydrogen sulfide content is about 800 ppm and scrubbing has never been used.

The digester gas is used primarily in 10 supercharged 8 cylinder Worthington engines rated at 1688 hp. The engines are dual fuel and continuously utilize about 5 percent fuel oil. Five of the engines operate generators each rated at 1190 kw. The other five engines are direct coupled to blowers each rated at 40,000 cfm. The engines are each equipped with heat recovery units which are used to heat the digesters. The data shows that about 40 percent of the installed capacity of 5950 kw was utilized in generating electricity (about 58,000 kwh/day).

Los Angeles County Sanitation District

The primary treatment plant for the Sanitation District treats an average of about 385 mgd and is equipped with 30 digesters. An average of 5.5 million cu ft of gas is produced and 16 cu ft per lb of VS destroyed. The digester gas is about 60 percent methane with a high heat value of 607 Btu. A summary of digester gas analyses from December 1973 through May 1975 is shown in Table 7. The lower heating value of the digester gas would be about 577 Btu per cu ft. This data also shows that the average hydrogen sulfide concentration was very low, about 28 ppm, with the highest figure reported to be 147 ppm.

Gas is transferred directly from the digesters to 12 Ingersoll-Rand engines without any treatment, compression or storage. The standby fuel is propane and the engines are not equipped with heat recovery units. There is an emergency waste gas burner on site, but normally any excess gas is taken by a contractor at $0.15 per 1,000 cu ft. Five of the engines are direct coupled to pumps rated at 97,000 gpm each; the other seven engines are connected to generators as follows:

Rated Engine, bhp	Rated Generation Capacity, kw
2 engines at 1180 each	835 each
1 engine at 1100	775
2 engines at 888 each	615 each
2 engines at 800 each	560 each
TOTAL 6836	4795

The engines operate at low rpm (330 to 360) and some have been operating for 20 years with no significant down time.

Orange County Sanitation District (California)

During the 1972-73 fiscal year digester gas production in two plants averaged 2,214,000 cu ft/day. The gas is used in (a) naturally aspirated internal combustion engines coupled to influent and effluent pumps, (b) boilers, and (c) rag incinerators. All engines are spark ignited with natural gas for standby fuel. Heat recovery systems on the engines are utilized to heat the digesters. The plant is also equipped with a gas turbine generator set which is used for standby power. The gas turbine is equipped with a heat recovery unit which furnishes steam to a turbine and another generator. This heat recovery system has not performed satisfactorily and has been removed from service.

TABLE 7
DIGESTER GAS ANALYSES
Los Angeles County Sanitation District

Date	No. Days Sampled	Average % CO_2	Average % CH_4	Average Btu/cu ft*
December 1973	17	36.9	59.9	607
March 1974	18	37.1	60.0	608
April 1974	22	37.0	59.8	606
May 1974	21	37.0	59.6	604
July 1974	21	36.4	60.0	608
August 1974	22	36.2	60.3	611
September 1974	18	36.0	60.3	611
October 1974	22	36.5	59.9	607
November 1974	16	37.2	59.8	606
December 1974	19	36.7	60.2	610
January 1975	22	36.8	60.0	608
February 1975	18	36.9	59.9	607
March 1975	21	37.2	59.6	604
April 1975	20	37.7	59.1	600
May 1975	21	37.2	59.6	604
AVERAGE		36.9	59.9	607

Note: Data from March 1974 through February 1975 indicates that the average H_2S concentration is 28 ppm$\pm$17 ppm. The highest figure reported for this period was 147 ppm or 0.015% by weight of a cubic foot of digester gas.

* Based on a higher heating value of 1013 Btu/cu ft

A 45 mgd activated sludge plant is currently under construction and two 1500 hp Enterprise-Delaval engines will be installed to drive blowers rated at 35,000 scfm at 7 psi discharge pressure. The engines will be spark ignited and will operate at 350 rpm. Two White Superior 1200 hp engines will be installed for effluent pumping and two 250 hp White Superior engines will be installed for in-plant pumping. Natural gas will also be the standby fuel for these new engines.

Gas withdrawn from each digester passes through a sediment trap and is conveyed to gas compressors. The compressors normally compress the gas to 40 psi with a maximum capability of 50 psi. Compressed gas is stored at a maximum pressure of 50 psi in two 32 ft diameter spheres (17,000 cu ft capacity). Gas pressure is reduced from the storage pressure of 40 - 50 psi to 2 - 5 psi prior to use in the engines, boilers and incinerators. The digester gas has a high hydrogen sulfide concentration of as much as 3,000 ppm, but scrubbers have never been used.

The District estimates that present work equivalent performed per day using digester gas as fuel amounts to 74,300 hp-hr. This amounts to 58 percent of the total energy required for collection and treatment based on actual work performed. Other energy sources used in the two plants are electrical, which accounts for 38 percent of the work and natural gas, which accounts for 4 percent.

Philadelphia, Pennsylvania

Digester gas is used to heat buildings and digesters, but no internal combustion engines are operated on digester gas. The gas is not cleaned, compressed or stored before use. A yearly average of 6.4 cu ft of gas is produced per lb of VS destroyed.

San Jose, California

The 160 mgd plant has eight primary digesters heated to 95^{o}F and three unheated secondary digesters. The digesters reduce VS by 50 to 55 percent. Primary digesters are heated with an external heat exchanger by hot water from internal combustion engine heat recovery units.

Average heat value of the digester gas is 550 Btu/cu ft and is mixed with natural gas to produce a blend with a heat value of 700 Btu/cu ft. No cleaning or scrubbing, except water removal, is provided. Digester gas is compressed to 60 psi before blending and no storage is provided before use in engines. Generally 85 to 90 percent of digester gas is used and 10 to 15 percent is flared.

The blended gas is used as fuel for 11 internal combustion engines. Five dual fuel Enterprise-Delaval engines drive electrical generators: 2 - 800 hp and 3 - 2500 hp. Six tri fuel spark ignited Cooper-Bessemer engines drive blowers: 3 - 2400 hp and 3 - 1800 hp.

Tucson, Arizona

Digester gas is used as fuel for 300 hp Waukesha internal combustion engines which are direct coupled to blowers. Data from the last two fiscal years was taken from the 1973-74 Annual Report and is summarized in Table 8. There is no explanation for the high gas production reported.

GAS PRODUCTION

Perhaps the most important design criterion that must be selected is the volume of gas produced per unit of organic material destroyed in the digester. Virtually all operating data, as well as data in the literature, is reported in cu ft of gas produced per lb of VS destroyed. In some cases the gas production is recorded in total lb of VS supplied to the digester. The EPA report by Smith[4] discusses the volume of gas produced as follows:

"The volume of gas produced per lb of VS destroyed is reported as 17-18 scf/lb at the larger and better instrumented plants. Smaller plants report lesser values, sometimes as low as 6 scf per lb VS destroyed, but these lower values are probably due to poor measurement techniques."

The Water Pollution Control Federation's Manual of Practice on Anaerobic Sludge Digestion[13] gives the following data on anaerobic conversions of the chief types of organic matter in sewage sludge:

Type and Average Concentration	Gas Produced (cu ft gas/lb organic matter digested)
Carbohydrate $(C_6H_{10}O_5)n$	14.2
Fat $C_{50}H_{90}O_6$	24.6
Insoluble Soap $Ca(C_{15}H_{31}O_2)_2$	22.3
Protein $6C \cdot 2NH_3 \cdot 3H_2O$	9.4

These data were developed from extensive experimental work conducted at the Los Angeles County Sanitation Districts.

The WPCF manual on sewage treatment plant design[8] gives the following gas production data:

"In terms of solids digested, the average yield adjusted to standard temperature of 60^{o}F is about 15 cu ft of gas per lb of VS destroyed. These gas volumes are for normal plant operating pressures of 6 to 8 inches of water."

The EPA Process Design Manual for Sludge Treatment and Disposal gives the following sludge and digester gas data:[14]

"In general, treatment of 1 mgd of municipal wastewater will provide 1 ton of mixed primary and activated sludge solids which translates to 0.2 to 0.3 lb solids/capita/day. An unheated digester will typically

TABLE 8

SUMMARY OF PLANT* OPERATIONS

Tucson, Arizona

	1972-73	1973-74
Population served	325,318	341,930
Average daily flow, mgd	33	32
Average influent suspended solids, mg/l	211	236
Average influent BOD , mg/l	227	235
Average suspended solids to digester, lb/day	38,192	35,589
Average volatile solids		
To digesters, percent of SS	72	79
To digesters, lb/day	27,452	28,137
Destroyed, lb/day	12,490	14,430
Reduction, percent	45.5	51.3
Average digester gas produced		
Thousand cfd	341,970	367,668
cu ft/lb volatile solids to digester	12.5	13.1
cu ft/lb volatile solids destroyed	27.4	25.5

*Sewage is treated in three plants: two activated sludge and one trickling filter.

produce 0.32 to 0.56 cu ft of gas/capita while a heated digester will produce from 0.56 to 0.74 cu ft of gas/capita. This is equivalent to a maximum gas production of approximately 11 to 12 cu ft of gas/lb of total solids digested. The heat value of sludge gas is approximately 566 Btu/cu ft."

A range of 14 to 19 cu ft of digester gas produced per lb of VS destroyed was reported for Chicago.[15]

Data collected from operating plants during this study indicates that 17 to 18 scf/lb of VS destroyed is not routinely obtained even at some well operated facilities and much lower values are reported in some presumably well operated plants. Therefore, 15 scf/lb VS destroyed is recommended for sizing typical digester gas utilization systems, unless data are available for a specific waste to be treated.

The amount of sludge produced in a wastewater treatment plant, the VS content of the sludge, and the gas produced by anaerobic digestion varies with influent suspended solids concentration, BOD and type and efficiency of the biological treatment processes. A published review[16] of sludge quantities produced in municipal wastewater treatment plants concludes that 915 and 1,085 lb/million gallons treated are typical quantities of sludge produced by primary and secondary treatment respectively. The following sludge quantities are based on a review of data from several sources and are considered representative of typical primary and activated sludge plants:

Sludge Solids
(lb/million gallons)

Sludge Type	Total	Volatile	Volatile (percent of total)
Primary	1,155	690	60
Waste Activated	945	756	80
TOTAL	2,100	1,446	69

A review of the literature, and data collected from operating plants during this study, indicates that about 50 percent of the volatile solids are destroyed by anaerobic digestion and that the gas produced has a heat value of about 600 Btu/scf.

These criteria give the following estimates for gas and heat available from anaerobic digestion:

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

For planning purposes, and in the absence of more specific information, it may be assumed that about 6.5 million Btu per million gallons of wastewater treated are available from gas produced by anaerobic digestion of sludge produced by primary and conventional activated sludge treatment.

GAS UTILIZATION

Digester gas can be used for on-site generation of electricity and/or for any in-plant purpose requiring fuel. Digester gas could also be used off-site in a natural gas supply system.

Off-Site Use

Off-site use of digester gas will usually require treatment to remove trace impurities such as hydrogen sulfide and moisture; in most cases the heat value of the digester gas must be increased by removal of carbon dioxide before it can be used in a natural gas system. Carbon dioxide removal is not commonly practiced at wastewater treatment plants but information on systems used in the chemical industry is available.[17] The estimated cost in 1974 to treat digester gas, from a 125 mgd plant in Dallas, Texas, for use in a natural gas system was $0.46 per 1,000 scf of methane.[18] This cost included a carbon dioxide removal system manufactured by Union Carbide that uses a monoethanolamine absorbent. In-plant energy requirements for primary and secondary treatment always exceed the energy available from digester gas; therefore, the remainder of this section is devoted to on-site use as fuel in internal combustion engines.

Use In Internal Combustion Engines

Diesel or gas internal combustion engines can be used to drive electric generators, air blowers or pumps in a wastewater treatment plant. A typical system illustrating these potential uses is shown in Figure 9.

Diesel engines operate on fuel oil that is ignited entirely by the heat resulting from the compression of the air supplied for combustion. Gas-Diesel engines operate on a combustible gas (anaerobic digester gas in this case) as primary fuel; the ignition of the digester gas is accomplished by the injection of a small amount of pilot fuel oil. Commonly 5 to 10 percent fuel oil is required to operate a dual fuel engine. Dual fuel Diesel engines are equipped to operate on fuel oil only or as a gas-Diesel. Fuel oil is normally used in the alternate fuel system for dual fuel engines in a wastewater treatment plant; however, it is possible to equip this type of engine to also operate on natural gas or propane.

A gas internal combustion engine operates on a combustible gas fuel (anaerobic digester gas in this case) that is ignited by an electric spark. Natural gas or propane could be used as an alternate source of fuel in a gas engine.

There are many variations in engine design, and auxiliary equipment required, for these two basic engine types. The operating speed and

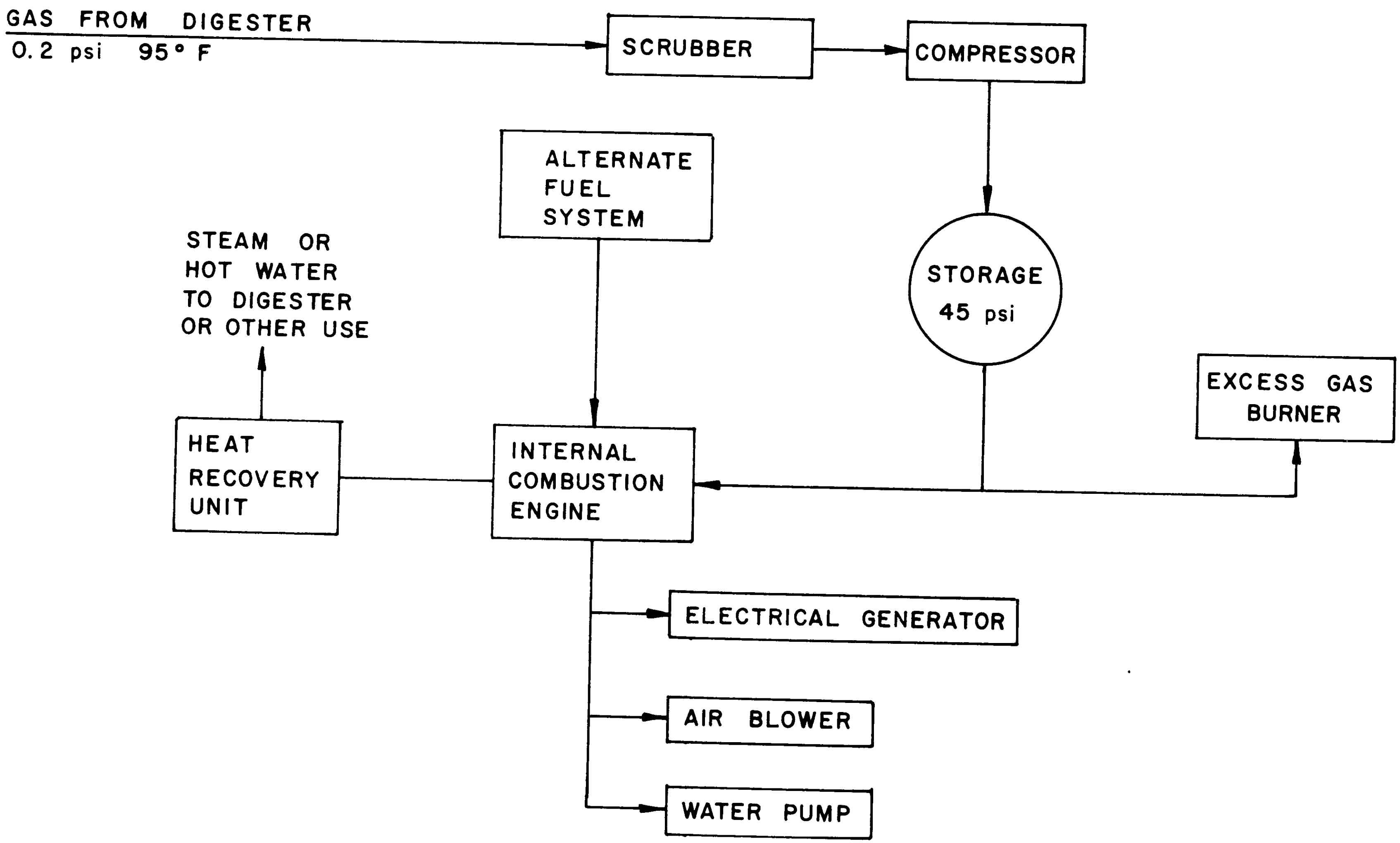


Figure 9. Anaerobic digester gas utilization system.

turbocharging are basic differences between engines supplied by different manufacturers. These variations in engine types result in equipment cost and operation and maintenance cost variations.

The efficiency of engines varies depending on the basic engine design and method of operation. In general, low speed, turbocharged or dual fuel engines require less fuel per hp-hr than higher speed naturally aspirated engines. However, capital costs are greater for the more efficient engines. Average efficiencies obtained at the Hyperion Treatment Plant during three years of operating 10 dual fuel engines are compared with other estimates in Table 9.

The use of heat recovery equipment will increase the overall efficiency. One manufacturer estimates energy supplied to internal combustion engines is used as follows:

	Energy Use (percent)
Jacket water and lube oil	45
Exhaust	15
Radiation	10
Work	30

Heat recovery has been used successfully for many years particularly with large slow speed engines. Typical heat recovery rates for dual fuel engines manufactured by White Superior are shown in Table 10. This data shows that recovered heat varies from 20 to 31 percent of fuel input. Typical heat recovery rates in percent of fuel supplied to the engine are: jacket water, 18 to 20 percent; exhaust, 10 to 13 percent; combination of both jacket water and exhaust heat recovery, 20 to 33 percent. This recovered heat added to the 30 to 37 percent efficiency of the engine results in a total thermal efficiency ranging from 50 to 70 percent.

One generally used method of recovering jacket water heat is through ebullient cooling, that is, raising the jacket water temperature to just above the boiling point (215^{o} to 220^{o}F) and collecting the steam in an external separator. The low pressure steam thus produced may be used for digester heating, sludge drying, building heating or other purposes. Exhaust heat is typically recovered by use of combination exhaust silencer and heat recovery boilers. In some installations the jacket water and exhaust heat are recovered in a single combined unit. The cost of heat recovery equipment varies considerably, but usually in proportion to the size of the engine, with lower unit costs for larger engines.

Table 11 is a summary of gas, heat and power available for various size treatment plants based on the following criteria:

1. Total dry solids to digester = 2,100 lb/million gallons and VS = 1,446 lb/million gallons from primary and conventional activated sludge treatment.

TABLE 9

INTERNAL COMBUSTION ENGINE EFFICIENCY OPERATING ON DIGESTER GAS

	Engine Rating (Btu/hp-hr)	Efficiency (percent)
Hyperion Plant		
1971-72	6469	39.4
1972-73	6428	39.6
1973-74	7675	33.2
EPA Report[4]	7000	36.4
Engine Manufacturers		
Caterpillar	8500	30.0
Delaval	6630	38.4
White Superior		
Gas fuel, naturally aspirated, spark ignited	8300	30.7
Gas fuel, turbo-charged, spark ignited	7700	33.1
Dual fuel	7000 (or less)	36.4

TABLE 10
TYPICAL HEAT RECOVERY RATES FOR DUAL FUEL ENGINES

Engine Size (kw)	Cycle	Type of Exhaust Manifold	Fuel Input (Btu/kwh)	Recovery At Full Load (Btu/kwh)				Overall Efficiency (Percent)
				Power	Jackets	Exhaust	Total	
1500-2000	4	Wet	9950	3563	1700	1400	6663	67
1000-1500	4	Dry	9950	3563	700	1900	6163	62
1000-2500	2	Dry	9520	3563	800	2100	6463	68
3000-6000	2	Dry	9450	3563	1180	700	5443	57

TABLE 11

ANAEROBIC DIGESTER GAS PRODUCTION AND USE

(1) Plant Capacity (mgd)	(2) Total Dry Solids to Digester (lb/day)	(3) Volatile Solids Destroyed (lb/day)	(4) Gas Produced (scf/day)	(5) Heat Available (mil Btu/day)	(6) Power Available From IC Engines (hp)	(7) Power Available From Engine-Generator set (kw)	(8) Heat Recovered From IC Engine (mil Btu/day)
1	2,100	723	10,845	6.5	38	24	1.6
5	10,500	3,615	54,225	32.5	190	120	8.1
10	21,000	7,230	108,450	65.0	380	240	16.2
25	52,500	18,075	271,125	162.5	950	600	40.6
50	105,000	36,150	542,250	325.0	1,900	1,200	81.2
75	157,500	54,225	813,375	487.5	2,850	1,800	121.8
100	210,000	72,300	1,084,500	650.0	3,800	2,400	162.5

Column (2) Primary and conventional activated sludge treatment
(3) Primary sludge solids 60% volatile, WAS 80% volatile; 50% volatiles destroyed
(4) 15 scf per lb VS destroyed
(5) Net heat = 600 Btu/scf (9,000 Btu/lb VS destroyed)
(6) Efficienty = 36.4%; 7000 Btu/hp-hr
(7) Efficiency = 30%; 11,400 Btu/kw-hr
(8) 25% recovery

2. Fifty percent of VS destroyed in digester.

3. Digester gas produced = 15 scf/lb VS destroyed

4. Heat available = 600 Btu/scf gas or 9,000 Btu/lb VS destroyed.

5. IC engine efficiency = 36.4 percent (7,000 Btu/hp-hr).

6. Engine-generator efficiency = 30 percent (11,400 Btu/hp-hr).

COST ESTIMATES - DIGESTER GAS UTILIZATION

Construction costs in this report include all elements of construction cost a contract bidder would normally encounter in furnishing a complete facility. Construction costs include materials, labor, equipment, electrical, normal excavation and contractor overhead and profit. Construction costs do not include costs for land, engineering, legal, fiscal and administrative services or interest during construction. Construction costs include the same elements included in construction costs in the Black and Veatch report.[12]

Equipment costs were obtained through quotes from various suppliers and manufacturers. Construction costs include allowances for the following: overhead and profit (25 percent), equipment installation (35 percent), electrical (15 percent), piping and miscellaneous items (15 percent) and, other site work and contingency (15 percent). Compounding these allowances gives a construction cost of 2.6 times equipment cost. Operation and maintenance is broken down into three categories: (1) operating and maintenance labor in hr/yr, (2) materials and supplies in $1,000 yr, and (3) energy in kwh/yr or Btu/yr.

Cleaning and Storing Digester Gas

Hydrogen sulfide (H_2S) can be removed from digester gas by treatment in a chemical scrubbing system using sodium hypochlorite or other oxidizing agents. The reaction with sodium hypochlorite requires 2.2 lb of NaOCI to remove one lb of H_2S:

$$H_2S + 4NaOCl \rightarrow H_2SO_4 + 4NaCl$$

It is possible to use activated carbon for H_2S removal but the carbon must be regenerated with steam. Chemical scrubbing systems are more economical and simpler to operate. It may be possible to use other chemicals, or other sources of hypochlorite, to furnish less expensive scrubbing systems than shown herein. Iron sponge scrubbers have been installed in some treatment plants.

Estimated construction costs and operation and maintenance data for compressors are shown in Table 12. Equipment costs are based on recent quotes from manufacturers, operation and maintenance estimates are based on records of the Orange County (California) Sanitation District.

TABLE 12

DIGESTER GAS COMPRESSION COSTS

Plant Capacity (mgd)	Gas Produced (scfm)	Equipment Available (scfm)	(hp)	(kw)	Construction Cost* ($1,000)	Operation and Maintenance Labor hr/yr	Material $1,000/yr	Electricity 1000 kwh/yr
1	7.3	---	---	---	---	---	---	---
5	36.5	50	15	11.2	52	185	1	98
10	73	100	20	14.9	57	370	2	131
25	183	200	30	22.4	65	740	5	196
50	365	350	50	37.3	91	1600	10	327
75	548	638	100	74.6	117	2300	15	654
100	730	1052	150	111.9	143	3000	20	980
200	1460	1402 (1052 +350)			234	4600	30	1307
300	2190	2104 (2 @ 1052)			286	6000	40	1960

*Cost includes skid mounting, all stainless steel trim on internal compressor parts, all belts, drive pulleys, guards, inlet filter, after cooler and TEFC electric motor.

Operating Conditions:

- 60^0 F Ambient temperature
- 14.7 psia inlet pressure
- 50.0 psig discharge pressure
- 0.8 Specific gravity digester gas

The following construction costs of conventional size spheres to store gas at 50 psi are based on a recent quote from a supplier in Southern California.

Sphere Diameter (ft)	Volume (cu/ft)	Construction Cost ($1,000)
32	17,000	65
36	24,000	90
46	50,000	185
60	113,000	400

Unit costs for diameters larger than 60 ft are higher because of structural features that must be incorporated.

Construction costs for scrubbing with NaOCl in a packed tower, include on-site hypochlorite generation. Operating and maintenance costs for this type of scrubbing system assume the removal of 1,000 ppm H_2S from the digester gas. The estimated construction costs to clean and store digester are summarized in Table 13. Construction costs are shown in Figure 10; operation and maintenance data are shown in Figure 11. Construction costs are greatly influenced by the storage capacity provided. The storage capacity used in these estimates is based on one sphere per plant, up to plant sizes of about 100 mgd.

On-Site Electricity Generation

The primary components of a system to generate electricity with digester gas, in addition to gas cleaning and storage facilities, are shown on the anaerobic digester gas utilization system schematic (Figure 9) and include: (1) IC engine, (2) generator, (3) heat recovery unit, and (4) alternate fuel system.

Cost estimates for electric power generation are based on the following criteria:

1. Engine and engine-generator equipment costs are based on data furnished by several major engine manufacturers: Ingersoll Rand, Enterprise Delaval, White Superior, Fairbanks Colt and Waukesha.

2. Both dual fuel and gas engine costs are included for equipment available in 600 rpm speeds.

3. Dual fuel engines are turbocharged and gas engines are naturally aspirated.

4. Engine costs include all auxiliary equipment required for an operating installation, such as: skid base, exhaust silencer, air inlet filter, starting equipment , gas and dual fuel pumps, regulators, safety devices, control equipment and main circuit breaker. Heat recovery units are shown as a separate item.

TABLE 13

DIGESTER GAS CLEANING AND STORAGE COSTS

Plant Capacity (mgd)	Scrub & Compress (scfm)	H_2S Removed @ 1000 ppm[1] (lb/day)	Gas Compressed[2] (1000 cu ft/day)	Scrub and Compress Construction Cost ($1000)	Storage Spheres			Cleaning and Storage System[3]			
					Volume (1000 cu ft)	Number & Diam (ft)	Construction Cost ($1000)	Construction Cost ($1000)	Labor (hr/yr)	Material ($1000/yr)	Energy (1000 kwh/yr)
5	50	5	24	88	17	1-32	65	153	240	2	142
10	100	10	48	99	24	1-36	90	189	470	4	219
25	200	25	96	117	50	1-46	185	302	1000	10	371
50	350	50	168	156	74	1-36 1-46	275	431	2000	20	634
75	640	75	307	205	113	1-60	400	605	2900	30	1092
100	1050	100	504	257	113	1-60	400	657	3750	40	1593
200	1400	200	672	367	226	2-60	800	1168	3750	60	2533
300	2100	300	1008	450	339	3-60	1200	1650	7500	80	3800

1 Assumes digester gas = 0.071 lb/cu ft

2 Gas compressed and stored @ 45 psi

3 Cleaning and Storage System includes scrubbers, compressors and storage spheres in a complete system

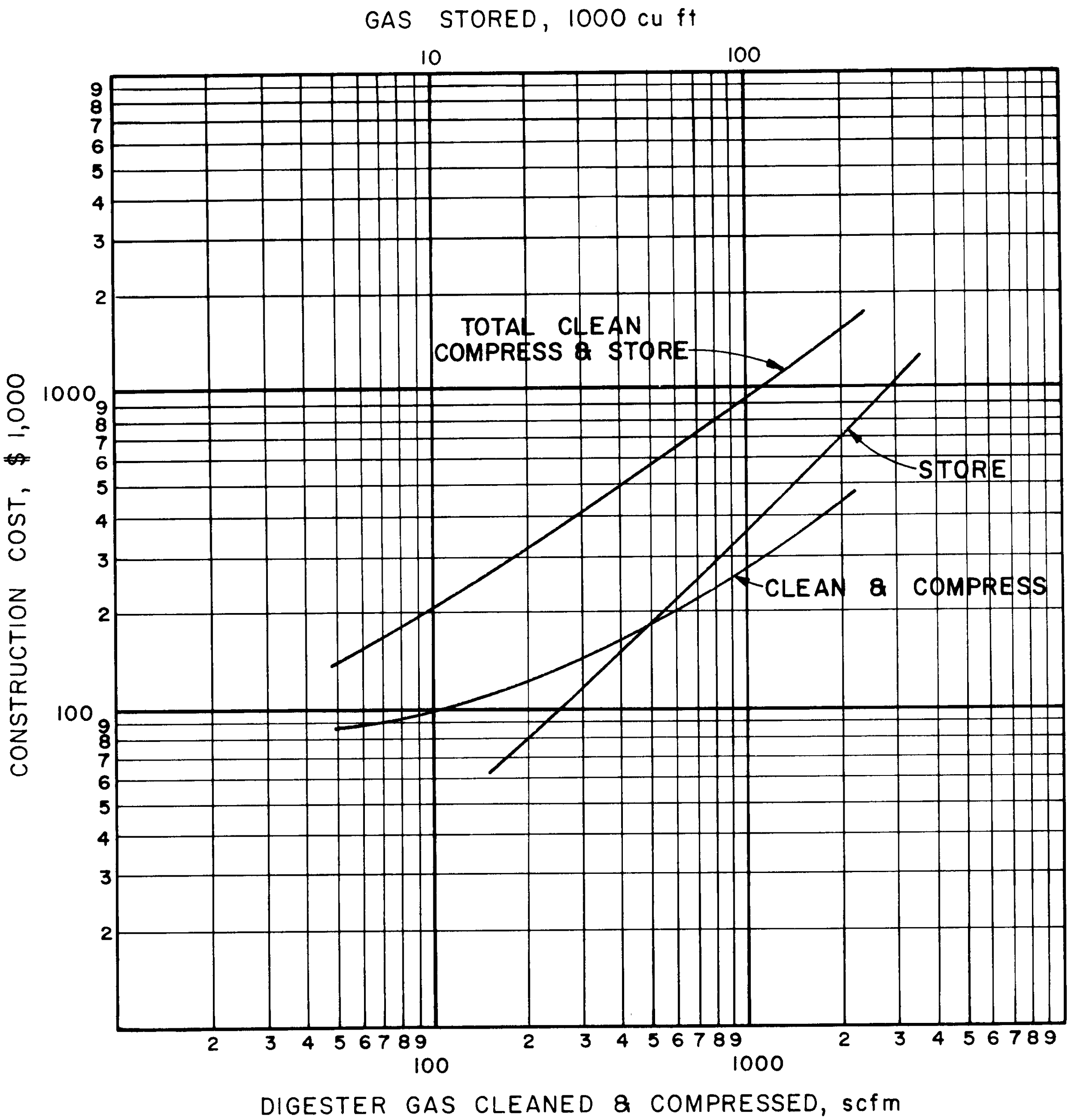


Figure 10. Construction cost to clean and store digester gas.

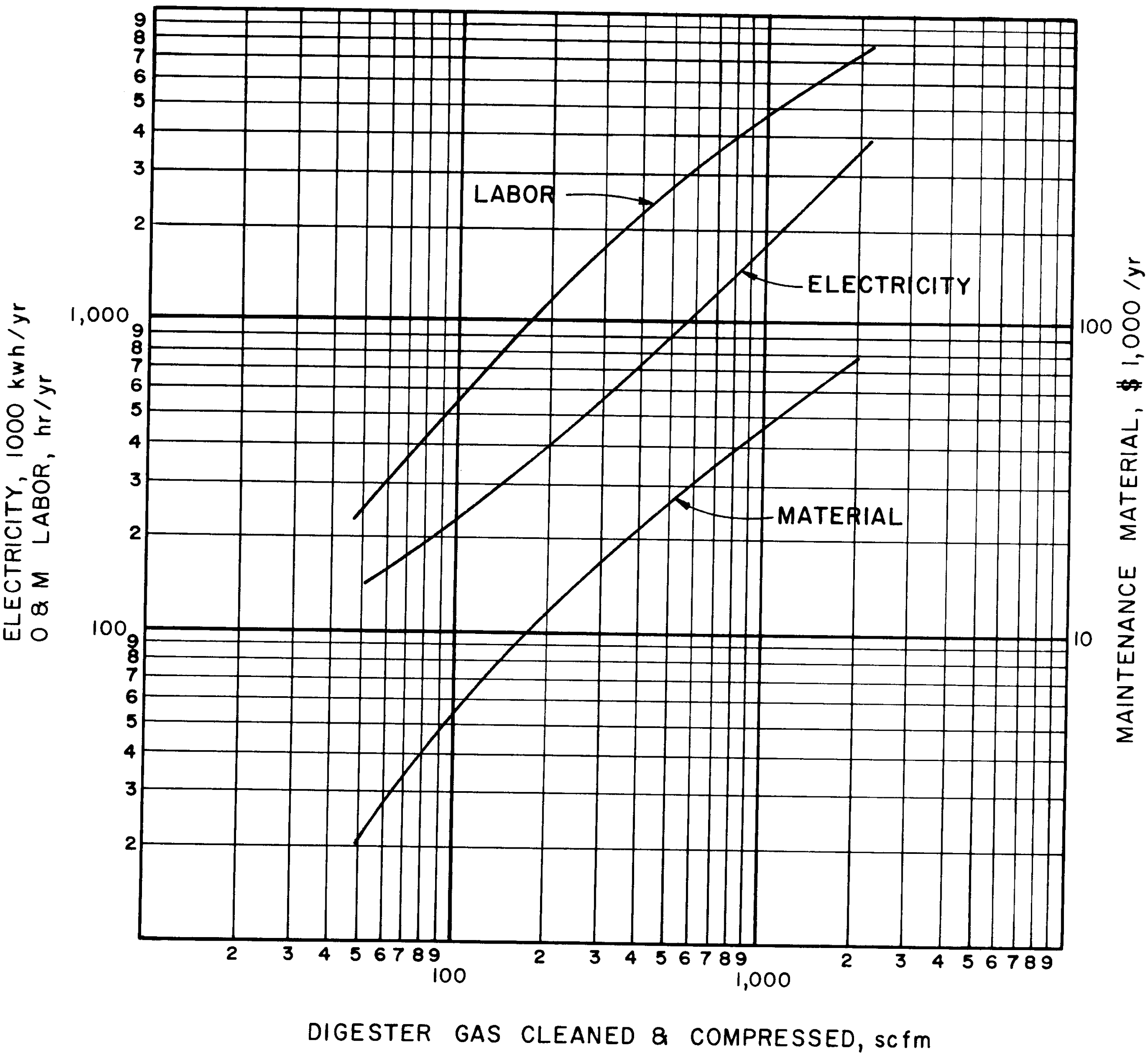


Figure 11. Operation and maintenance costs to clean and store digester gas.

5. Alternate fuel systems are fuel oil for dual fuel engines and propane for gas engines.

Fuel oil:	142,500 Btu per gal
Propane :	91,500 Btu per gal

6. Heat recovery costs are based on ebullient systems and data furnished by Vaporphase Systems and the engine manufacturers.

7. Operation and maintenance estimates are based on a detailed analysis of four years data from the Orange County Sanitation District for six engines operating on digester gas.

Estimated costs for 600 rpm internal combustion engines equipped with heat recovery and alternate fuel systems are shown in Figures 12 and 13. These cost curves include data for both dual fuel and gas engines. Operation and maintenance costs are greatly affected by the alternate fuel consumed. Propane alternate fuel systems are more costly than fuel oil systems; however, gas engines that would require propane are less costly than dual fuel engines that require fuel oil. Dual fuel engines require about 10 percent fuel oil on an average annual basis. Gas engines could operate without using any alternate fuel. However, for these estimates, it is assumed that 10 percent would be consumed. Propane would have to be used (or at least paid for) to obtain contracts for a firm supply.

Estimated costs for complete systems to generate electricity with digester gas are shown in Figures 14 and 15. These costs are for a system as shown in Figure 11.

<u>Example Cost Estimate</u>

The cost curves may be used to estimate on-site electricity generation costs as shown in the following example for a 100 mgd plant:

Construction cost (Figure 14)	\$2,500,000
Material (Figure 14)	55,000/yr
Labor (Figure 15)	5,800 hr/yr
Electricity (Figure 15)	1,500,000 kwh/yr
Fuel (Figure 15)	23 x 10^9Btu/yr

Annual costs:

- Construction — \$319,000 per year

  \$2,500,000 plus 35 percent for engineering, administration, interest during construction and other costs = \$3,375,000 total. Amortize for 20 years at 7 percent interest, (\$3,375,000) (0.09439) = \$319,000

- Operation and Maintenance — \$220,000 per year

  Labor 5,800 hr @ \$10/hr — \$58,000

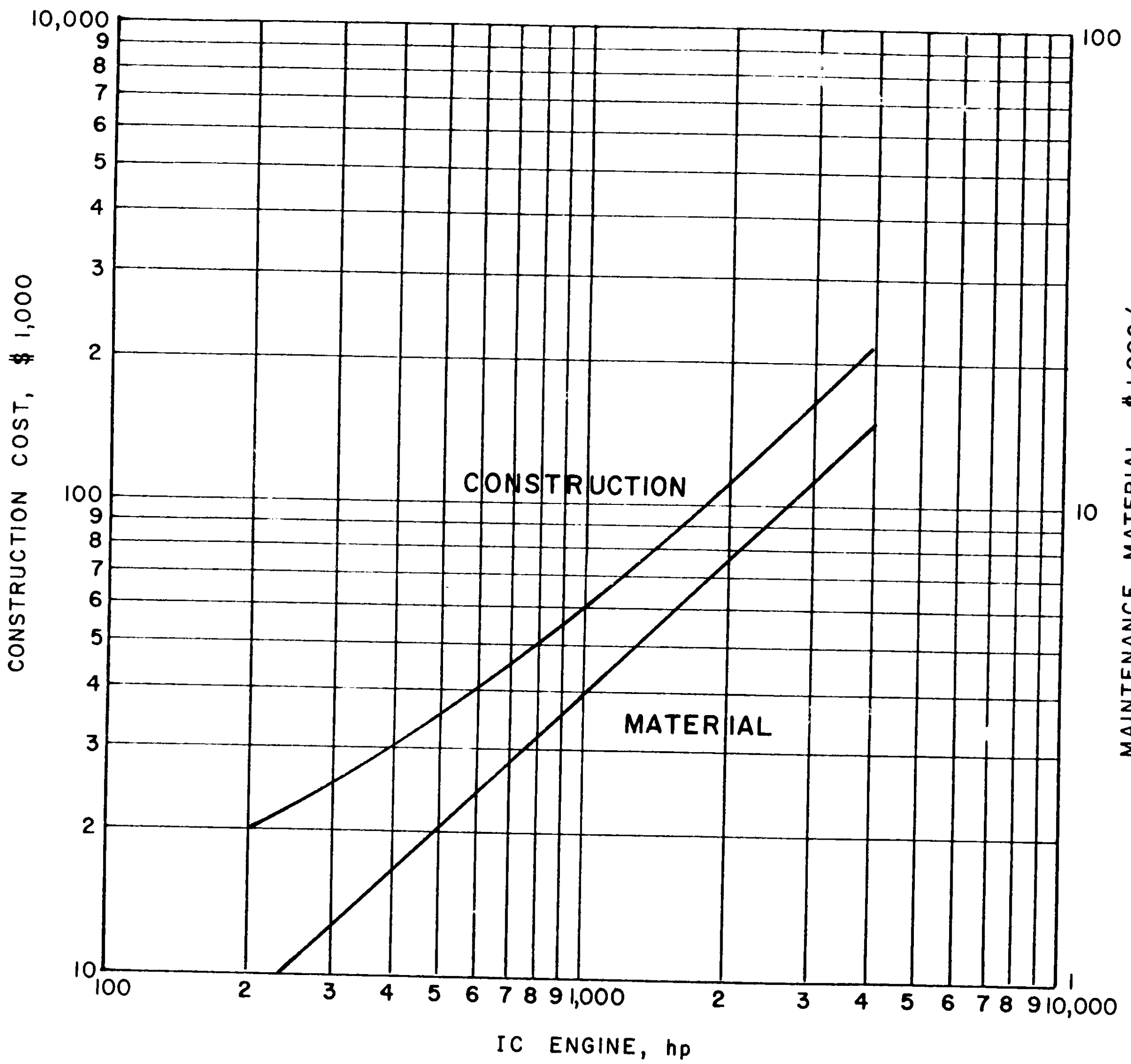


Figure 12. Construction and maintenance material costs for 600 rpm IC engines with heat recovery and alternate fuel systems.

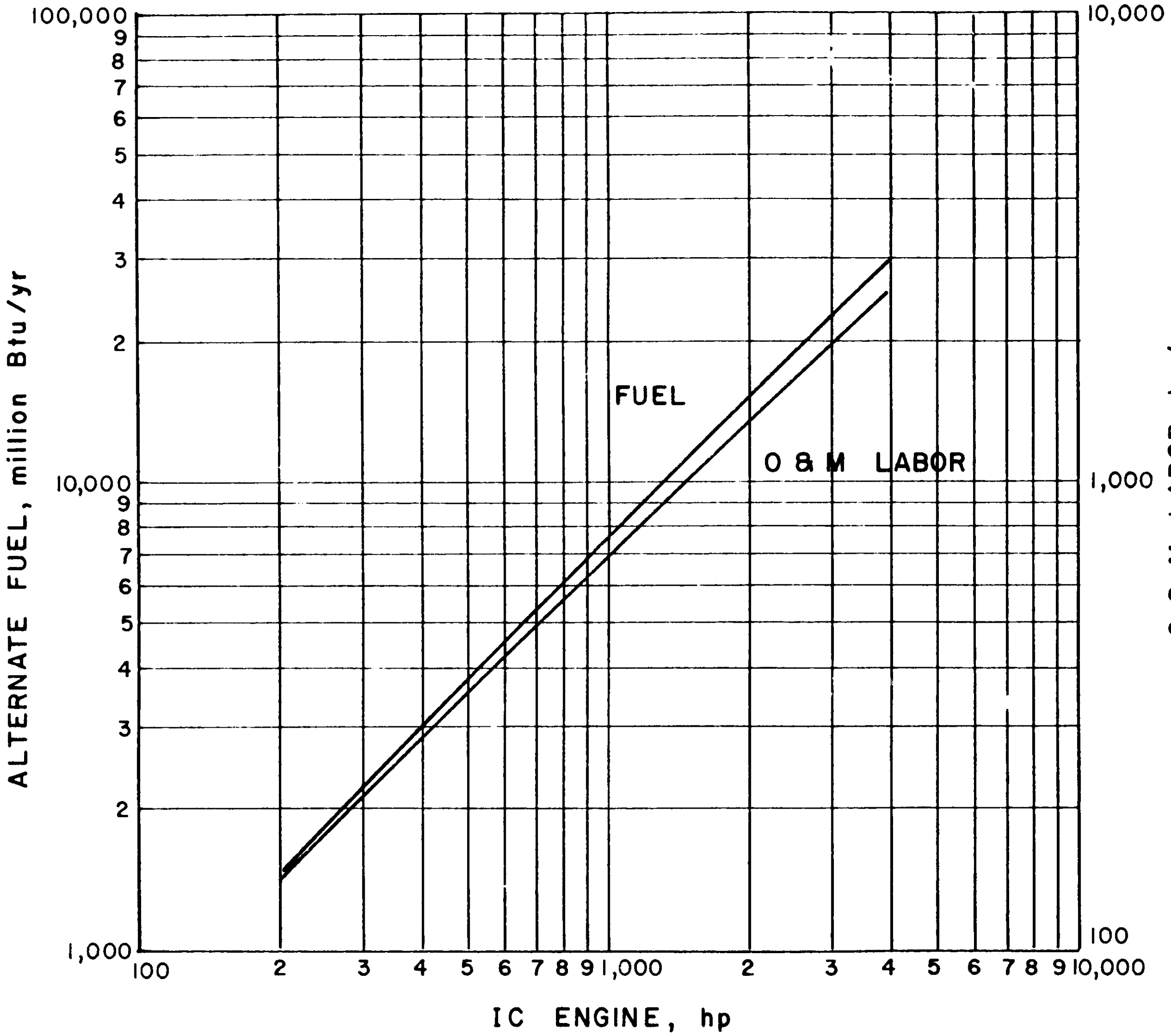


Figure 13. Alternate fuel and labor requirements for 600 rpm IC engines with heat recovery and alternate fuel systems.

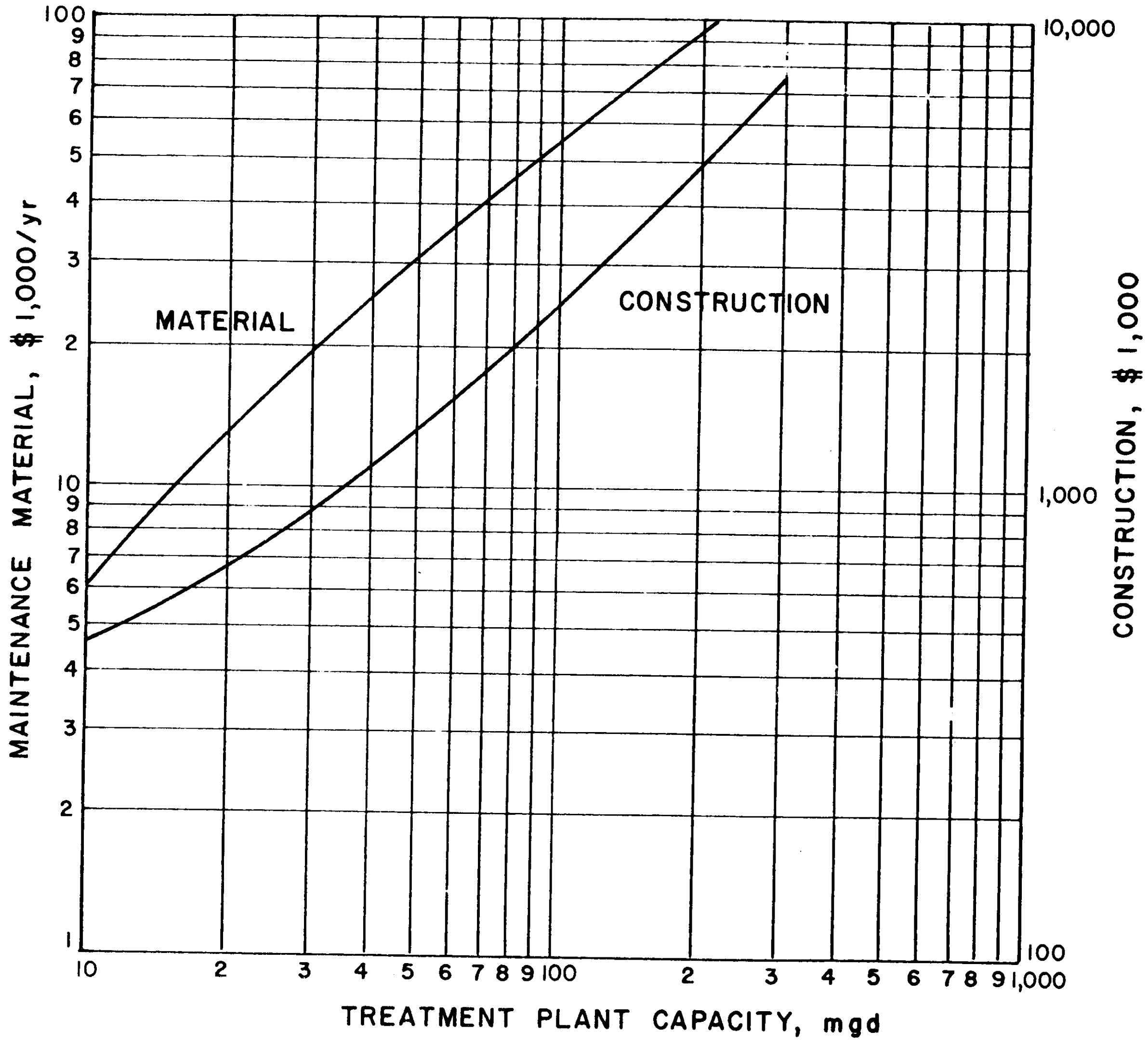


Figure 14. Construction and maintenance material costs for complete electrical generation system shown in Figure 9.

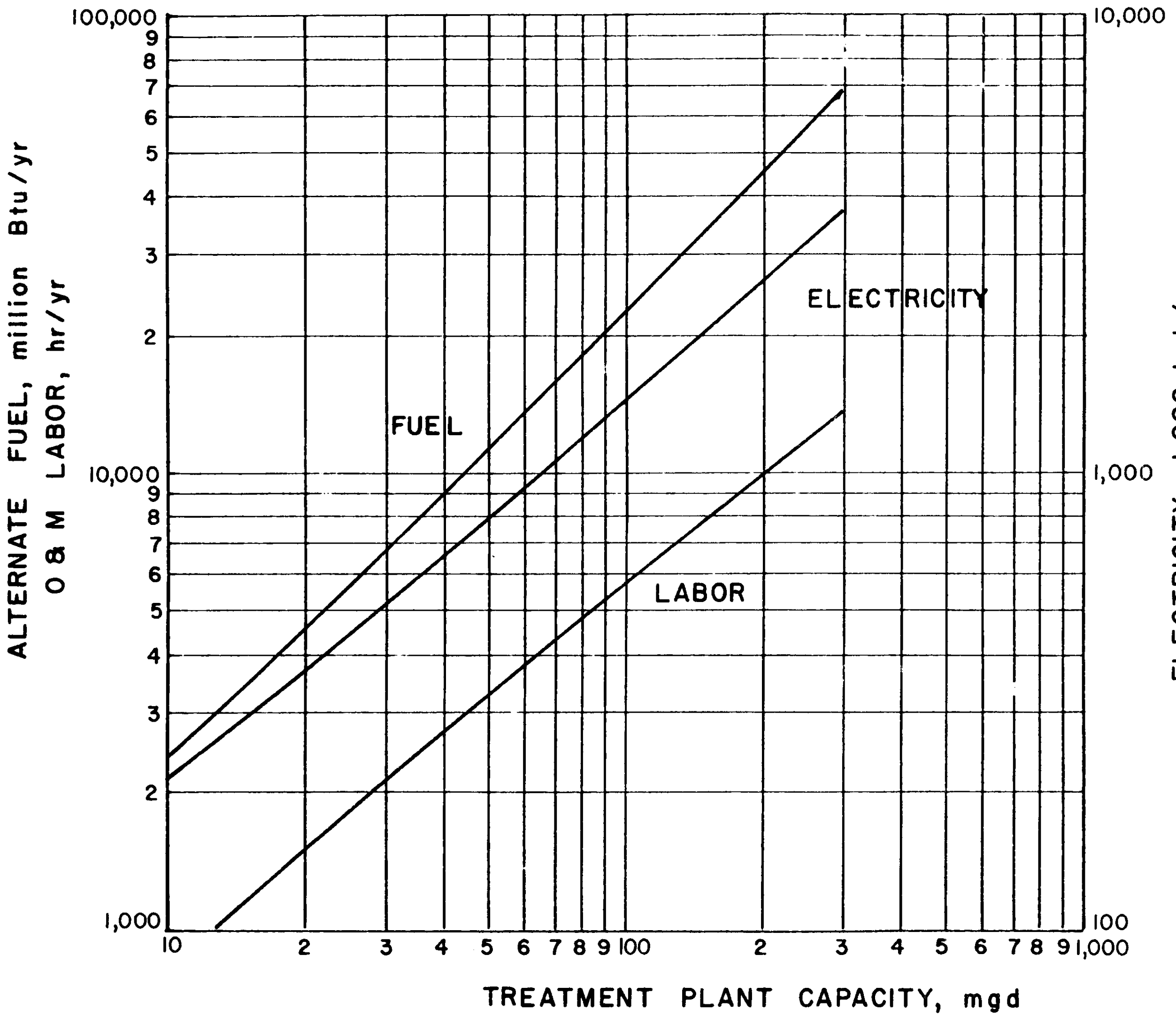


Figure 15. Labor and energy requirements for complete electrical generation system shown in Figure 9.

Material	\$55,000
Electricity 1,500,000 kwh @ \$0.025/kwh	38,000
Fuel 23×10^9 Btu/yr @ \$3/mil Btu	69,000

- Total Annual Cost \$539,000 per year

Column (7) in Table 11 estimates that there are 2400 kw (21,000,000 kwh/yr) available from a 100 mgd plant. This gives a unit electricity generation cost of \$0.026 per kwh. If the generating facility operates only 80 percent of the time, the unit cost increases to \$0.032/kwh. These costs do not take credit for recovered heat. Column (8), Table 11 estimates that 162.5 mil Btu/day (59×10^9 Btu/yr) could be recovered in a 100 mgd plant. Valuing this waste at \$1.50/mil Btu reduces the unit costs to \$0.022/kwh and \$0.028/kwh for 100 percent and 80 percent operating time respectively. A similar calculation for 10 mgd plant, including credit for recovered heat, gives \$0.037 and \$0.047 per kwh for 100 percent and 80 percent operating time respectively.

SECTION 5

PRODUCTION OF CONSUMABLE MATERIALS

Estimated energy requirements are presented for off-site production of the following consumable materials:

Activated Carbon	Lime(Calcium Oxide)
Alum	Methanol
Ammonium Hydroxide	Oxygen
Carbon Dioxide	Sodium Chloride
Chlorine	Sodium Hydroxide
Ferric Chloride	Sulfur Dioxide
	Sulfuric Acid

Data on energy required to manufacture consumable materials was obtained from several sources including: (1) contact during this study with manufacturing companies, (2) technical journals and books, and (3) calculations based on descriptions of production processes contained in the technical literature or furnished by manufacturers.

Specific energy requirements for some materials are somewhat difficult to obtain for the following reasons:

1. Some companies consider this type of information proprietary and will not release details of the manufacturing process or the energy required. Other companies could not, or would not, furnish energy data for a variety of reasons including the belief that it would jeopardize their competitive position, and insufficient records.

2. Some manufacturing processes produce more than one product, e.g., chlorine and sodium hydroxide, or a primary product and a by-product e.g., ammonia and carbon dioxide.

3. By-product or waste from one process used as feedstock in manufacturing process, e.g., ferric chloride and sulfuric acid.

4. Most chemicals are produced by more than one process, or with different methods of obtaining feedstock, with different energy requirements, e.g., sulfuric acid, carbon dioxide and methanol.

The estimated energy requirements for production are summarized in Table 14. These total energy estimates include the fuel required to generate electricity required for production.

The following sections discuss the energy estimates for each consumable. List prices for each chemical were used as a general guide to the reasonableness of the estimates. The following costs and other factors were used in developing the energy estimates:

TABLE 14

ESTIMATED ENERGY REQUIREMENTS FOR THE PRODUCTION OF CONSUMABLE MATERIALS

Material	Fuel Million Btu/ton	Electricity kwh/lb
Activated Carbon	102*	4.9
Alum	2*	0.1
Ammonium Hydroxide	41*	2.0
Carbon Dioxide	2 to 54	0.1 to 2.6*
Chlorine	42	2.0*
Ferric Chloride	10	0.5*
Lime (Calcium Oxide)	5.5*	0.3
Methanol	36*	1.7
Oxygen	5.3	0.3*
Salt (Sodium Chloride)		
Evaporated	4*	0.2
Rock & Solar	0.5	<0.1*
Sodium Hydroxide (50% NaOH)	37	1.8*
Sulfur Dioxide	0.5	<0.1*
Sulfuric Acid	1.5*	0.1

* Indicates principal type of energy used in production.

Electricity	$0.028/kwh
Natural Gas	$1.30/million Btu
Fuel	
Natural gas	1,000 Btu/cu ft
Coal	25,000,000 Btu/ton
Diesel fuel	142,500 Btu/gal
Electricity generation	10,500 Btu/kwh (32.5% efficiency)
Steam generation (low pressure)	1,600 Btu/lb

ACTIVATED CARBON

The manufacture of activated carbon is a highly competitive industry and the companies will not divulge specific details of their production process nor will they furnish information on the energy required for production. There are several books devoted to activated carbon,[19, 20, 21] but none contain information on energy requirements for manufacturing.

Regarding the manufacture of granular carbon for water treatment Hassler,[20] notes:

"The production of granular carbons for liquid phase applications was long delayed because of the additional activation necessary to provide the required types of adsorptive capacity. The additional activation oxidized the walls of pores and thereby weakened the structure. As a result, the finished carbons lacked the mechanical strength to withstand the abrasion incident to continual recycling required of granular carbons. The difficulty was finally surmounted about the time of World War II. Granular carbons with effective adsorptive capacity combined with adequate mechanical strength have been available for liquid systems for a number of years."

The granular activated carbon now used in most reactivation systems throughout the world is made from bituminous coal.

Powdered carbon is made from granular activated carbon by grinding the dry granular material. Hassler[20] describes the preparation of powdered carbon as follows:

"The preparation of powdered carbon should be accomplished by the mildest possible pulverizing action. A powerful crushing action as by heavy weights of balls in a ball mill can damage the filterability. It can also impair the adsorptive power of decolorizing types of carbon.

Carbons should preferably be very dry when pulverized because the presence of moisture augments adverse effects of filterability."

The common requirements of all the processes for the production of activated carbon are that the raw material is carbonized at temperatures usually in the 500 to 800°C range and then activation is achieved either by the addition of reagents to the raw material or by a subsequent activation stage. In processes involving gaseous activation with steam or carbon dioxide, the activating reaction is endothermic. If, however, the product gases are burned to provide heat, the overall reaction is merely the combustion of part of the carbon which is an exothermic reaction. Carbons used in wastewater treatment are activated with heat and steam and thus fuel(usually natural gas) is required for the activation process. Hassler[20] describes the process as follows:

> *"In a typical process, coal is pulverized and mixed with sufficient binder to form a plastic mass which is briquetted or extruded at pressures variously described ranging from 100 to 2,000 lbs per square inch. The pellets or spaghetti-like strings are carbonized slowly to avoid rapid evolution of gas, after which the char is steam activated."*

A report by one manufacturer[11] states that 12.8 million Btu are required to produce 250 lb of new carbon, or about 51,000 Btu/lb (102 million Btu/ton). The following are reported by Smisek and Cerny[21] to be the normal consumption of material and energy for the production of one ton of carbon activated with steam when wood charcoal is used as the starting material:

Wood-tar	1,500 kg
Wood-Charcoal	3,000 kg
Steam	10,000 kg
Electricity	2,000 kwh

These requirements would give about 10,500 Btu/lb for electricity and 17,000 Btu/lb for steam for a total of about 27,500 Btu/lb (55 million Btu/ton). This total does not include any energy required in the carbonization process to produce the wood charcoal.

Garber, et al.,[22] estimate the energy required to produce one ton of granular activated carbon as follows:

	Btu/ton Carbon
Mining and transporting coal	140,000
On-site production	36,000,000
TOTAL	36,140,000

The list price of wastewater treatment grade granular activated carbon is about $0.45/lb ($900/ton). The cost of natural gas for granular activated carbon manufacture would range from $0.023/lb (at 18,000 Btu/lb) to $0.066/lb (at 51,000 Btu/lb).

The higher energy requirement (51,000 Btu/lb) and energy cost does not appear unreasonable. Since the higher estimate is from a manufacturer and there is no data to support a lower figure, 51,000 Btu/lb (102 million Btu/ton) is shown in Table 14. There is no basis for differentiating between energy required for powdered and granular carbon production.

ALUM

Aluminum sulfate is produced by reacting bauxite ore ($Al_2O_3 \cdot 2H_2O$) or clays which are rich in aluminum oxide with sulfuric acid. The reaction is represented by the following formula:

$$Al_2O_3 \cdot 2H_2O + 3H_2SO_4 \rightarrow A_2(SO_4)_3 + 3H_2O$$

The process used for aluminum sulfate production is well-established and fairly standard among producers. It requires 670 lb bauxite (55 percent Al_2O_3) and 1,140 lb sulfuric acid (60°Be) to produce one ton of aluminum sulfate (17 percent Al_2O_3).[23]

Information furnished by three manufacturers ranged from 125,000 to 770,000 Btu required to produce one ton of alum. One manufacturer reported a total requirement of 4.7 million Btu/ton with 83 percent of the heat requirement supplied as a by-product of sulfuric acid manufacture. The report by Garber, et al.,[22] estimates an energy requirement for alum production of 9.2 million Btu/ton. Adding the energy required for sulfuric acid production (1.5 million Btu/ton) to the high figure reported by a manufacturer, gives a requirement of about 1.6 million Btu/ton.

The chemical reaction is exothermic and it appears that relatively small amounts of energy are required in subsequent processing operations; therefore, an energy requirement of 2.0 million Btu/ton appears adequate for production, including energy required for feedstocks.

AMMONIUM HYDROXIDE

Ammonium hydroxide, or aqua ammonia as it is termed commercially, is commonly produced in solutions varying from about 20 to 30 percent ammonia through the reaction of ammonia gas with water:

$$NH + H_2O \leftrightarrows NH_4OH \rightleftarrows NH_4^+ + OH^-$$

Ammonia is produced by the catalytic reaction of nitrogen and hydrogen at high temperature and pressure. The nitrogen is derived from air by means of liquefaction, the producer gas reaction, or by burning out the oxygen in air with hydrogen. Hydrogen is obtained from many sources, including water gas, coke-oven gas, natural gas, fuel oil, catalytic reformer gases, and the electrolysis of water or brine. Since World War II, natural gas has become the most important hydrogen source. Currently, petroleum or natural gas-derived ammonia represents 90 percent of production and ammonia is the number one petrochemical in terms of volume of production. Natural gas curtailments have reduced ammonia production since 1972.

Faith[23] gives the following requirements for producing one ton of liquid ammonia:

Natural gas (92% CH_4)	26,000 cu ft
Catalyst for shift reaction	0.3 lb

Synthesis catalyst	0.5	lb
Caustic soda (100%)	8	lb
Monoethanolamine	0.3	lb
Fuel gas (for driving compressors)	22,000,000	Btu
Electricity	108	
Water	6,000	gal

These feedstocks, fuel and electricity result in a total energy requirement of about 48 million Btu/ton of liquid ammonia produced.

A survey of energy use in the industrial chemicals industry by Saxton, et al.,[24] found that the average energy required for the production of ammonia in 1971 and 1973 was about 41 million Btu/ton. This total energy requirement is divided between feedstock energy (about 55 percent) and process energy fuel and electricity (about 45 percent).

The cost of energy supplied by natural gas would be about $62.40/ton for an energy requirement of 48 million Btu/ton. The cost of process energy, and energy represented by natural gas feedstock is about 38 percent of the list price for ammonia hydroxide.

CARBON DIOXIDE

Pure liquid or solid carbon dioxide (CO_2) is produced from various sources of dilute CO_2. Primary sources of dilute CO_2 gas include:

(1) gases from the decomposition of carbonates, and (2) combustion of coke, oil and natural gas. The resulting gases, ranging in CO_2 content from about 10 to 40 percent, are treated by absorption to remove CO_2. After the concentrated gas is purified, it is compressed and refrigerated to give liquid or solid CO_2. Coke, oil, and natural gas are burned carefully to produce a gas containing 17 to 18 percent CO_2, and the heat obtained is converted into energy for the compressors.

Because the thermal decomposition of limestone, dolomite, magnesite, marble, and similar materials yields gases containing 32 to 42 percent CO_2, by-product recovery is often carried out on kiln gases at cement and lime plants. When limestone or dolomite is used as a raw material, however, about 250 lb of coke is ordinarily mixed with every ton of limestone burned to effect fuel economy. Many of the new anhydrous ammonia plants have CO_2 recovery facilities.

The following are material and utility requirements reported by Faith[23] to produce one ton solid CO_2 from 18 percent flue gas:

		Energy Btu/ton Solid CO_2
Natural gas	22,000 cu ft	22,000,000
Sodium carbonate	25 lb	
Water	20,000 gal	

			Energy Btu/ton Solid CO_2
Steam	20,000 lb		32,000,000
Electricity	10 kwh		105,000
		TOTAL	54,105,000

These material and utility requirements result in a total energy requirement of about 54,000,000 Btu, at a cost of about $70, to produce one ton CO_2.

Data was furnished by three CO_2 manufacturers. One manufacturer reported that CO_2 gas is a by-product of ammonia production and is liquefied and sold. This company reported an energy requirement of 200 kwh/ton to liquefy the CO_2. Another large producer also reported that CO_2 was a by-product of other chemical manufacturing processes and they had no way to estimate the energy required for its production. The third manufacturer reported a requirement of 160 kwh/ton of CO_2 produced. A study for the Ford Foundation[25] estimated 40 kwh/ton CO_2 produced. Based on this data, a range of 2 to 54 million Btu per ton is shown in Table 14. The high value represents the total energy required to produce CO_2 from all new materials. Carbon dioxide used in wastewater treatment will often be produced at the plant site with purchased CO_2 use limited to standby and emergency purposes.

CHLORINE

Over 95 percent of the chlorine now manufactured in the United States is produced from the electrolysis of brine by two different methods: (1) diaphragm cells, and (2) mercury cells. The production of one ton of chlorine, in addition to electricity, requires about 3,660 lb sodium chloride, steam and refrigeration. The process also produces about 2,285 lb of sodium hydroxide and 57 lb of hydrogen gas per ton of chlorine produced.[25,26]

The gas produced at the anode is about 97.5 percent chlorine. The diaphragm cell produces an 11 to 12 percent solution of sodium hydroxide while the concentration is about 50 percent in the mercury cell method. Therefore, no evaporation is needed in a mercury cell to produce the usual commercial strength of 50 percent caustic. Despite this advantage, the use of mercury cells is being discontinued because of mercury in the waste discharge.

Typical electrical power requirements for diaphragm and mercury cells are reported by White:[26]

	kwh/lb Chlorine Produced
Diaphragm cells	1.36 - 1.41
Mercury cells	1.47 - 1.57

Chlorine gas produced in a diaphragm cell must be cooled, dried, compressed, scrubbed of impurities and liquefied by refrigeration for shipment. All of these operations consume energy, which is not included in the 1.36 to 1.41 kwh/lb shown above. However, the process also produces sodium hydroxide and some energy use should be charged to this chemical.

The survey of energy use in industrial chemical production by Saxton[24] gives a national average energy requirement to manufacture chlorine of 43.3 million Btu/ton in 1971 and 41.5 million Btu/ton in 1973. The Ford Foundation study[25] reports about 42 million Btu required to manufacture one ton dry chlorine and 1.13 tons caustic soda in 50 percent solution by the diaphragm cell process.

One manufacturer reported a requirement of 9,600 Btu/lb of chlorine produced and two others reported about 21,000 Btu/lb. The higher values also include steam for evaporation to produce a 50 percent solution of sodium hydroxide in the diaphragm cell method.

Power and salt required for the on-site generation of sodium hypochlorite are reported by several manufacturers as follows:

Manufacturer	Electrical Energy kwh/lb Chlorine Equivalent	Salt lb/lb Chlorine Equivalent
Ionics	1.6 - 2.5	1.8 - 2.0
Englehard	1.7 - 2.8	3 - 4
Pacific Engineering	2.3 - 3.0	3.2
Diamond Shamrock	2.5	3.5

An average electrical energy requirement for chlorine production of 2.0 kwh/lb is shown in Table 4-1 (this converts to 42 million Btu/ton using 10,500 Btu required to generate one kwh). The 2.0 kwh/lb includes necessary feedstocks, the electrolytic cell and other required processes and no credit for the sodium hydroxide and hydrogen produced.

FERRIC CHLORIDE

Little information was obtained from manufacturers on the processes used for ferric chloride production. One producer in Southern California manufactures ferric chloride using waste pickling liquor from a nearby steel mill. This particular mill uses hydrochloric acid for steel cleaning; the waste acid and ferrous chloride is supplied to the chemical producer. The waste is neutralized, concentrated by solar evaporation and reacted with chlorine solution to form ferric chloride.

$$FeCl_2 + \tfrac{1}{2} Cl_2 \rightarrow FeCl_3$$

Sulfuric acid is used in many steel manufacturing pickling operations. The reaction with waste pickle liquor from this type of operation is:

$$3FeSO_4 + 1\tfrac{1}{2}Cl_2 \rightarrow Fe_2(SO_4)_3 + FeCl_3$$

The stoichiometric reaction with ferrous chloride requires 437 lb chlorine to produce one ton of ferric chloride. An energy requirement of about 9.2 million Btu/ton for production of ferric chloride is given by this reaction by using an energy requirement for chlorine production of 2.0 kwh/lb. The reaction with ferrous sulfate would require 1,312 lb chlorine to produce one ton of ferric chloride and the energy requirement would be about 4,000 kwh/ton.

The 1976 price of ferric chloride was $80 to $100 ton with $90 per ton quoted in California. The 1976 price of chlorine was quoted at $125 to $150 per ton. However, some agencies in Southern California are paying $220 per ton for chlorine delivered in one ton cylinders. A manufacturing process to produce one ton ferric chloride would require chlorine with a list price of $25 to $48; a process starting with ferrous sulfate would require chlorine valued at $75 to $145.

The current price of ferric chloride appears consistent with a manufacturing process utilizing ferrous chloride as feedstock. Energy required for production by this method would be about 0.5 kwh/lb including feedstocks and processing energy

LIME (CALCIUM OXIDE)

Quick lime (CaO) is produced by burning various types of limestone ($CaCO_3$) in shaft or rotary kilns as illustrated in the following reaction:

$$CaCO_3 \xrightarrow{\text{heat}} CaO + CO_2 \uparrow$$

Shaft kilns are directly fired by oil, natural gas or producer gas. Rotary kilns are also fired with oil, natural gas or producer gas, but the trend has been to firing with pulverized coal. The modern trend is to large rotary kilns with capacities of at least 200 tons/day. Energy required to manufacture quick lime depends upon: (1) raw material, (2) type of furnace, (3) type of fuel, and (4) efficiency of equipment.

Shaft kilns are considered more efficient in terms of fuel economy than are rotary kilns. The most modern shaft kilns may approach a fuel ratio of 5 tons of lime per ton of coal and for the larger rotary kilns this ratio may average around 4.2. The national average for all quick lime production is about 7 million Btu/ton of quick lime. This may drop into the 5 million range as the larger kilns, both shaft and rotary, come on stream and the smaller, less efficient, kilns are retired.

The following requirements to produce one ton of quick lime were reported by Faith, et al.,[27] and one manufacturer:

Limestone (pure)	3,750 lb
Coal (bituminous)	650 lb

Using a heat value for coal of 12,500 Btu/lb gives 8.1 million Btu required to produce one ton of quick lime plus energy used in mining and delivering limestone.

The Flintkote Company, U.S. Lime Division, recently began operating a coal fired, rotary kiln in Nelson, Arizona, rated at 800 tons pebble quick lime per day. Initial operating results indicate that this new and efficient plant will require about 4.5 million Btu to produce one ton of quick lime. Another new plant is under construction in Kentucky which will be equipped with three 1,000 ton/day kilns. Estimates are that this plant will require from 4.5 to 5.2 million Btu to produce one ton of quick lime.

A report by the Stanford Research Institute[28] gives 5.6 million Btu required to produce one ton of lime. It appears that in modern plants about 5.5 million Btu should be adequate to produce one ton of quick lime, including limestone production.

METHANOL

Methanol is synthesized by the reaction of hydrogen and carbon monoxide under high pressures:

$$CO + 2H_2 \rightarrow CH_3OH$$

This reaction has an efficiency of about 60 percent without recycle. The reactants are obtained by a variety of methods from different raw materials. The most critical raw material for production in the United States is natural gas. Natural gas which has been desulfurized by passage over activated carbon is preheated and mixed with carbon dioxide and steam at 30 psig. The mixture is passed into heated alloy-steel tubes in a furnace. The tubes are normally packed with a promoted nickel catalyst. The reaction which takes place at 800°C is essentially:

$$3CH_4 + CO_2 + 2H_2O \rightarrow 4CO + 8H_2$$

The resulting synthesis gas is cooled by passage through waste heat boilers, various heat exchangers, and water coolers.

A few plants produce methanol by using carbon dioxide instead of carbon monoxide:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

One manufacturer reported a total energy requirement of 30 million Btu/ton for production of methanol including methane feedstock, steam and electricity. Another manufacturer reported 15 million Btu/ton including all steam used in the process.

The survey of energy use in industrial chemical production by Saxton[24] gives a national average energy requirement to manufacture methanol of 37.0 million Btu/ton in 1971 and 35.8 million Btu/ton in 1973. This total energy requirement is divided between feedstock energy (about 72 percent) and process energy (about 28 percent).

Because of the differences in manufacturing methods, the 1973 national average of about 36 million Btu/ton is shown in Table 14 for methanol.

OXYGEN

Pure oxygen is produced by the liquefaction and subsequent fractionation of air. Several different variations of the basic process are used by manufacturers including variations in the methods for air compression, purification, and refrigeration; and differences in the design of heat-exchange, rectifying, evaporating, and condensing equipment. The pressures of the various cycles range from about 60 to 3,000 psi.

Union Carbide Corporation is one of the largest producers and employs two basic oxygen generator designs. The cryogenic process is used in large installations and a pressure swing adsorption (PSA) system is used in smaller plants (usually less than 50 tons per day). The average power requirement for oxygen generation for each system is reported by Union Carbide[29] as follows:

PSA - 0.35 hp/lb O_2 transferred/hr at 90% oxygen utilization
Cryogenic - 0.22 hp/lb O_2 transferred/hr at 90% oxygen utilization

At a constant load, cryogenic oxygen systems use the least power for oxygen generation; however, the PSA unit turns down more linearly.

The Union Carbide system proposed for Amherst, Massachusetts would require 3720 hp-hr to generate six tons oxygen per day, or 620 hp-hr (470 kwh) per ton. A 350 ton/day system proposed for the City of Los Angeles would require 345 kwh/ton. Another manufacturer reported 500 kwh/ton required to generate oxygen gas and 800 kwh/ton for liquid oxygen.

Faith,[27] gives a range of energy requirements for oxygen production from about 290 kwh/ton in a 300 to 500 ton/day plant to 370 kwh/ton in a 25 ton/day plant. Another review of chemical technology[30] reports energy requirements for oxygen production of 500 kwh/ton for gas and 800 kwh/ton for liquid. The Ford Foundation study[25] estimates energy required for oxygen production of 425 kwh/ton for gas and 780 kwh/ton for liquid.

All of these reported requirements are in the range of 290 to 800 kwh/ton. It appears that 500 kwh/ton can be achieved in even small to medium size plants and this value is shown in Table 14. Pure oxygen use in wastewater treatment is similar to the use of carbon dioxide in that oxygen will most often be produced at the plant site.

SODIUM CHLORIDE

Sodium chloride is produced commercially in the United States by essentially three processes:

1. Multiple effect evaporation (evaporated salt) - 99.8 percent NaCl
2. Mining (rock salt) - 98.5 percent NaCl
3. Solar evaporation (solar salt) - 95 percent NaCl

Salt required for regeneration in selective ion exchange processes can be supplied by any of these three manufacturing methods. One manufacturer reported energy requirements for all three processes:

	kwh/ton Salt Produced
Evaporated salt (vacuum pan method)	2,340
Rock salt	22
Solar salt	150

Another manufacturer reported a steam requirement of 2,000 lb/ton. Using 1600 Btu/lb steam gives an energy requirement of 3.2 million Btu/ton. Faith[27] gives the following requirements to produce one ton evaporated salt (99.8 percent NaCl):

Saturated brine	7,600 lb
Soda ash (58%)	7.5 lb
Caustic soda (50%)	0.8 lb
Steam (actual)	2,500 lb (with triple effect evaporation)

The energy requirement would be about 4 million Btu/ton for steam, plus brine pumping. Estimated energy requirements are shown in Table 14 for all three types of salt.

SODIUM HYDROXIDE

In the electrolytic process for the manufacture of sodium hydroxide, an electric current is passed through a cell containing a sodium chloride solution. The salt brine is decomposed by the current to form a 10 to 70 percent sodium hydroxide solution, with hydrogen gas forming at the cathode and chlorine gas at the anode as co-products. Two types of cells, the mercury cathode and diaphragm, are used in the United States. These are the same units used to produce chlorine gas.

Mercury cells produce sodium hydroxide of 20 to 70 percent concentration and diaphragm cells produce a 10 to 12 percent solution. The weak solutions are concentrated in multi-effect evaporators to produce a 50 percent standard grade solution.

Four manufacturers furnished data on energy required for production of sodium hydroxide ranging from 0.9 to 2.1 kwh/lb. Data in the Chlorine section indicates that about 42 million Btu are required to produce 1.13 tons of sodium hydroxide, in 50 percent solution, and one ton chlorine.

Sodium hydroxide is also produced commercially from lime and soda ash according to the following reaction:

$$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$$

In this process, a solution of sodium carbonate (soda ash) is treated with calcium hydroxide (hydrated lime) to produce a precipitate of calcium carbonate and an aqueous solution of sodium hydroxide. After removal of the insoluble carbonate, the solution is concentrated to give various grades of caustic soda. Material and utility requirements to produce one ton sodium hydroxide (11 percent solution) by this method are:

Sodium carbonate (58 percent)	3,000 lb
Lime (make-up - 98 percent CaO)	165 lb
Water	2,200 gal
Steam	2,700 lb
Fuel (reburning)	13,000,000 Btu
Electricity	18 kwh

The manufacture of caustic soda is related both to the chlorine industry and to the ammonia-soda industry in that it is produced as a profitable item by both. In the first case, caustic soda is a joint product with chlorine; in the second, production is secondary to soda ash. The percentage of total production manufactured by the electrolytic process was 29 percent in 1925, 44 percent in 1935, and more than 85 percent in 1954. Demand for chlorine is increasing faster than demand for caustic soda. There is a definite tendency for chlorine consumers to build electrolytic plants to supply their own chlorine needs and to market excess caustic.[27]

The energy requirement shown in Table 14 is on the same basis as that shown for chlorine (1 ton chlorine and about 1.13 ton of sodium hydroxide are co-products in the electrolytic process). The 37 million Btu is the energy required to produce one ton of sodium hydroxide; this same 37 million Btu would also produce 1750 lb chlorine and 50 lb hydrogen.

SULFUR DIOXIDE

Sulfur dioxide (SO_2) is the basic raw material for the manufacture of sulfuric acid and SO_2 for this purpose is derived from several sources including:

1. Sulfur. Burning with the proper ratio of air yields a gas which is 8 to 11 percent SO_2.

2. Metal sulfides. Heating ferrous sulfides (FeS_2 or Fe_7S_8) releases SO_2. The remaining iron oxides may be utilized as iron ore in some cases. The sulfur must be driven off of the sulfides of copper, lead, nickel and zinc that are mined for their metal content. Air pollution control laws now require smelters to remove SO_2 from the stack gas discharge.

3. Hydrogen sulfide. H_2S recovered in the production of fuel gases can be burned directly to SO_2. In one process the H_2S is stripped from the fuel gas with an ethanolamine solution and later liberated from the solvent. The concentrated H_2S is then converted to SO_2 by burning at 1000^oC in a pressurized boiler where 80 percent of the total heat of reaction can be recovered by generating steam.

Energy required for production of SO_2 varies depending upon the manufacturing process and the source of feedstock. Gases containing SO_2 are cooled, purified and liquefied by compressing. Production by a process similar to that used for CO_2 would require about 200 kwh/ton plus feedstock requirements. Sulfur mined by the Frasch process requires about 8 million Btu/ton for hot water and pumping energy while several of the other feedstock sources are waste gases from other processes.

It is noted in the Ford Foundation study[25] that compound gas (acetylene and carbon dioxide) require much less energy for production than elemental gases (oxygen, nitrogen and hydrogen). One manufacturer reported that more energy is recovered by waste heat boilers in the production process than is used in purification and liquefaction. Another manufacturer considers the production energy requirement to be about 150 Btu/ton for liquefaction. An energy requirement of 0.5 million Btu/ton is considered representative for SO_2 production and is shown in Table 14.

SULFURIC ACID

Sulfuric acid is produced commercially in the United States by two basic methods: (1) contact process, and (2) chamber process. Very few new chamber plants have been constructed since the advent of the contact process.

Both the contact and chamber processes for producing sulfuric acid utilize sulfur dioxide as the basic raw material. The primary difference in the processes is the method of oxidizing the sulfur dioxide to sulfur trioxide. However, the chamber process can more easily use sulfur dioxide of low purity and may, therefore, be better adapted to producing sulfuric acid from pyrites and waste gases.

Faith[27] gives the following requirements to produce one ton sulfuric acid (100 percent H_2SO_4) in plants with 50 ton/day capacity:

	Contact Process	Chamber Process
Sulfur, lb	688	677
Water, gal	4,000	2,500
Air, cu ft	250,000	275,000
Electricity, kwh	5	15

The electrical energy required to produce sulfuric acid from sulfur dioxide ranges from 5 to 15 kwh/ton. The sulfur dioxide can be produced from several sources as described in the previous section.

One manufacturer reported a production energy requirement of 1 million Btu/ton. Another manufacturer reported 2.6 million Btu/ton. These figures include sulfur dioxide production by burning sulfur but do not include energy required for sulfur production. As noted in the previous section on sulfur dioxide, heat is produced and recovered in the sulfur burning process.

The study of energy use in industrial chemicals production by Saxton[24] gives about 160,000 Btu/ton for sulfuric acid manufacture. This does not include the energy consumed in mining sulfur. This study also notes that a great deal of excess steam is available from sulfuric acid plants because of the heat released when sulfur is burned in air.

An energy requirement of 1.5 million Btu/ton is considered adequate for sulfuric acid manufacture, including energy required for all raw materials, with the exception of sulfur production by the Frasch process. More total energy would be consumed by plants using native sulfur mined by the Frasch process (not considering heat recovery) and less energy would be required by plants using waste gases as a sulfur source.

REFERENCES

1. Huffman, G. L., "Effects of Pollution Control on the Demand for Energy," paper presented at California Water Pollution Control Association Meeting, San Jose, California, April 15, 1974.

2. Voegtle, J. A., "Be Conservative About Energy," JWPCF Deeds and Data, February, 1975.

3. Eilers, R. G. and Smith, R., "Executive Digital Computer Program for Preliminary Design of Wastewater Treatment Systems," Water Pollution Control Research Series WP-20-14.

4. Smith, R., "Electrical Power Consumption for Municipal Wastewater Treatment," EPA-R-2-73-281, July 1973.

5. ASHRAE Guide and Data Book, Fundamentals for 1965 and 1966, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. N.Y.

6. Morgan, M. Granyer, "Energy and Man: Technical and Social Aspects of Energy," IEEE Press, N.Y., 1975.

7. "Operation of Wastewater Treatment Plants," WPCF Manual of Practice No. 11, 1970.

8. "Sewage Treatment Plant Design," WPCF Manual of Practice No. 8, 1967.

9. "Operation of Wastewater Treatment Plants," WPCF Manual of Practice No. 11, 1976.

10. Evans, D. R. and Wilson, J. C., "Capital and Operating Costs - AWT," Journal WPCF, Vol. 44, No. 1, pp. 1-13, January 1972.

11. Bernardin, F.E., Jr., and Petura, J. C., "Energy Considerations in Adsorption as a Wastewater Renovation Technique," Second National Conference on Water Reuse, Chicago, May 4-8, 1975.

12. Patterson, W. L. and Banker, R. F., "Estimating Costs and Manpower Requirements for Conventional Wastewater Treatment Facilities," EPA Water Pollution Control Research Series 17090 DAN, October 1971.

13. "Anaerobic Sludge Digestion," WPCF Manual of Practice No. 16, p. 7, 1968.

14. "Process Design Manual for Sludge Treatment and Disposal," EPA 625/1-74-006, pp. 5-17. October 1974.

15. Graef, Steven P., "Anaerobic Digester Operation at the Metropolitan Sanitary Districts of Greater Chicago," Proceeding of the National Conference on Municipal Sludge Management, Pittsburgh, Pa., June 11-13, 1974.

16. Kormanik, Richard A., "Estimating Solids Production for Sludge Handling," Water and Sewage Works, pp. 72-74, December 1972.

17. Strelzoff, S., "Choosing the Optimum CO_2 Removal System", Chemical Engineering, pp. 115-120, September 15, 1975.

18. "Digester Gas Reclamation, City of Dallas Central Wastewater Treatment Plant", Black and Veatch, 1974.

19. Mantell, C. I., "Carbon and Graphite Handbook," Interscience Publishers, New York, 1968.

20. Hassler, J. W., "Purification With Activated Carbon," Chemical Publishing Company, New York, 1974.

21. Smisek, M. and Cerny, S., "Active Carbon, Manufacture, Properties and Applications," Elsevier Publishing Co., New York, p. 41, 1970.

22. Garber, W. F., et al., "Energy-Wastewater Treatment and Solids Disposal," Journal of the Environmental Engineering Division, ASCE, Vol. 101, No. EE3, Proc. Paper 11357, pp. 319-332, June 1975.

23. Lowenheim, F. A. and Moran, M. K., "Faith, Keyes and Clarks's Industrial Chemicals," Fourth Edition, John Wiley and Sons, Inc., New York, 1975.

24. Saxton, J. C., et al., "Industrial Energy Study of the Industrial Chemicals Group," International Research and Technology Corporation, NTIS PB - 236322, August, 1974.

25. "Energy Comsumption in Manufacturing," report to the Energy Policy Project of the Ford Foundation, Ballinger Publ. Co., Cambridge, Mass., 1974

26. White, G. C., "Handbook of Chlorination," Van Nostrand Reinhold Co., 1972.

27. Faith, W. L., et al., "Industrial Chemicals," Second Edition, John Wiley and Sons, Inc., New York, 1957.

28. Stanford Research Institute, "Patterns of Energy Consumption in the United States," U. S. Government Printing Office, p. 152, January, 1972.

29. "Comparison of Fundamentals, Design Parameters, and Operational Characteristics of Air and Oxygen Activated Sludge Systems," Union Carbide Corp., Linde Division, Environmental Systems Department (undated).

30. "Chemical Technology: An Encyclopedic Treatment," Volume I, Barnes and Noble, New York, 1968.

METRIC UNIT CONVERSION FACTORS

English Unit	Multiplier	Metric Unit
Btu	1.055	kJ
Btu/lb	2.326	kJ/Kg
cu ft	0.12832	l
cu yd	0.765	m^3
^oF	0.555 (^oF - 32)	^oC
ft	0.3048	m
gal	3.785	l
gpd/sq ft	0.04074	$m^3/m^2 \bullet d$
gpm	0.06308	l/s
gpm/sq ft	0.67902	$l/m^2 \bullet s$
hp	0.7457	kw
hp-hr	2.685	MJ
in.	25.4	mm
lb (mass)	0.4536	kg
mil gal	3785	m^3
mgd	3785	m^3/d
ppm (by weight)	essentially	mg/l
psi	6.895	kN/m^2
sq ft	0.0929	m^2
tons (short)	907.2	kg

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-77-214	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE ENERGY REQUIREMENTS FOR MUNICIPAL POLLUTION CONTROL FACILITIES		5. REPORT DATE November 1977 (Issuing Date)
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) G. M. Wesner		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Culp/Wesner/Culp Clean Water Consultants Santa Ana, California 92707		10. PROGRAM ELEMENT NO. 1BC611
		11. CONTRACT/GRANT NO. Cont. No. 68-03-2186
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research & Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES
Project Officer: Francis L. Evans, III
EPA-MERL-WRD, Cincinnati, Ohio 45268, 513/684-7610

16. ABSTRACT

This report presents information on energy requirements in municipal pollution control facilities for several major areas of interest.

1. Pumping energy for filtration and granular carbon adsorption of secondary effluent - Pumping requirements are developed for all elements of the filtration process including: (a) main stream, (b) backwash, (c) surface wash, (d) wash water return, and (e) chemical feed.

2. Heat Requirements - Estimated heat requirements are developed for:

(a) Building heat. For three cities, heating requirements are presented as a function of plant capacity.

(b) Anaerobic digestion. Heat requirements for anaerobic digestion at 95°F in standard and high rate digesters are given as a function of influent sludge temperature.

(c) Heat treatment of sludges. Fuel requirements as a function of thermal treatment capacity are presented for both heat conditioning prior to dewatering and for oxidation prior to ultimate disposal.

3. Utilization of Anaerobic Digester Gas - Cost estimates are presented for cleaning and storing digester gas, and for use as fuel in internal combustion engines that are coupled to pumps, blowers or electrical generators.

4. Secondary Energy Requirements - Estimations are made for off-site production ~~of some of the consumables used in wastewater treatment processes.~~

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Waste treatment, Sewage filtration, Sludge digestion, Activated carbon, Drying, Energy, Power, Pumping, Heat, Heating load, Heat recovery, Conversion, Cost analysis, Cost estimates	Energy requirements, Digester gas (cleaning, storage, reuse), Pumping energy--filtration, Granular carbon adsorption, Secondary energy requirements--consumables	13B

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 85
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1978— 757-140/6631