United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-78-149
August 1978

Research and Development

Total Energy Consumption for Municipal Wastewater Treatment

EPA-600/2-78-149
August 1978

TOTAL ENERGY CONSUMPTION FOR MUNICIPAL WASTEWATER TREATMENT

by

Robert Smith
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

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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.

The increasing cost of energy and the potential for shortages of fossil fuels in the future has created a keen interest in methods available for minimizing energy consumption by conservation or recovery of energy from waste materials. A vital part of this initiative is to quantify energy used for all forms of human activity. This report attempts to quantify the total energy used in collecting and treating municipal wastewater. An effort is also made to show the effectiveness of measures which might be used to conserve energy and to recover it from the residuals produced at the wastewater treatment plant.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Quantities of all forms of energy consumed for collection and treatment of municipal wastewater are estimated. Heat energy is equated to electrical energy by a conversion factor of 10,500 Btu/kwh. Total energy consumption, expressed as kwh/mg of wastewater treated, ranges from 2300-3700 kwh/mg. Energy used for construction of the treatment plant and the sewerage system represents 35-55% of the total energy consumed. The remainder used for plant operation is predominately (65-75%) electrical energy. The use of high efficiency aeration devices combined with good maintenance practices appears to offer the best opportunity for conservation of energy within the plant. Recovery of energy from the sludge produced at the plant can be accomplished by anaerobically digesting the sludge and using the digester gas as fuel for internal combustion engines. In large plants, when the sludge is sufficiently dewatered, it is also possible to recover energy by incinerating the dewatered sludge with production of steam in a waste heat boiler. The steam can then be used within the plant or expanded through a steam turbine to produce mechanical or electrical energy.

This report covers the period January 1, 1977 to January 1, 1978, and work was completed as of January 1, 1978.

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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

Btu	-- British thermal unit (1 Btu = 1055 joules)
kwh	-- kilowatt-hour
mg	-- million gallons (1 mg = 3785 cu meters)
DVS	-- dry volatile solids
mgd	-- million gallons per day (1 mgd = 0.0438 cu m/sec)
IC	-- internal combustion (engines)
scf	-- standard cubic foot
psig	-- pounds per square inch gage (1 psig = 0.0703 kg/sq cm)
bbl	-- barrel (1 bbl = 42 gallons = 0.15987 cu m)
ton	-- 2000 lb (1 ton = 907.2 kg)
cu yd	-- cubic yard (1 cu yd = 0.7646 cu m)
hp-hr	-- horsepower-hour (1 hp-hr = 0.746 kwh)

SYMBOLS

MGD	-- millions of gallons per day
TDH	-- total dynamic heat, ft or meters of water
AEF	-- aeration efficiency, percent of supplied air dissolved in water or pounds of oxygen dissolved per kwh or hp-hr utilized
SRT	-- sludge retention time (days) defined as the mass (lb) of activated sludge held in the process divided by the wasting rate (lb/day)

SECTION 1

INTRODUCTION

Since the national energy awareness was heightened by the Arab oil embargo between October 1973 and March 1974, much has been written about consumption of energy in municipal wastewater treatment plants and the potential for conservation or recovery of energy. Energy used for operating wastewater treatment plants is known to be small compared to other national energy consuming activities. For example, electrical energy used in plants has been estimated (1) at 1-2% of the average residential consumption and only about 0.17% (2) of the total national energy use. Although these comparisons might suggest that energy usage, and thus the importance of conservation and recovery, in wastewater treatment plants is relatively trivial, this is definitely not true in terms of the annual plant operating budget. The likelihood of substantial increases in the cost of energy over the useful life of the plant and the possibility of local shortages of some forms of energy are factors which should not be neglected in planning the processing scheme to be used at the plant.

Although much has been written about energy consumption for collection and treatment of municipal wastewater, there is a need to clearly delineate the total and operating energy budgets and to quantify the potential for conservation and recovery of all forms of energy. This report will begin by estimating the magnitude of the major consumptive uses of energy such as energy for construction of plants and collection systems, electrical energy for plant operations, energy for off-site manufacture of chemicals used in plant operation, heat for plant buildings, and the consumption of heat energy for processes such as anaerobic digestion and incineration.

Using the total or operating energy budget as a basis, the potential for energy conservation or energy recovery within the plant will then be examined in order that the relative value and importance of alternative energy saving measures might be clarified and put into perspective. Although energy occurs naturally in many forms, the energy consumed for operating wastewater treatment plants is primarily hydraulic energy for pumping water or air and heat energy used by processes such as anaerobic digestion or incineration of sludge. The efficiency of pumps and blowers is usually in the range of 70-80% so that mechanical energy can be converted to hydraulic energy with no more than about 30% loss. Similarly, mechanical and electrical energy can be converted from one form to the other with a loss of less than 10%. On the other hand, the conversion of heat energy to mechanical energy necessitates the wasting of roughly 2/3 of the heat energy.

For example, if electrical energy is converted to heat energy, one kilowatt-hour will generate about 3413 Btu of heat. However, if heat energy is used to generate electrical energy in a modern coal fired power plant, about 10,500 Btu of heat energy is needed to generate one kilowatt-hour. To clarify the discussion of energy consumption, all energy forms will be converted to electrical energy and expressed as kilowatt-hour per million gallons of water treated.

SECTION 2

CONCLUSIONS

Estimates of 1 total energy and 2 energy used for plant operation are shown in Tables 1 and 2 respectively, for activated sludge treatment of municipal wastewater. Heat energy has been converted to electrical energy by assuming that one kwh is equivalent to 10,500 Btu.

It can be seen from Table 1 that roughly one-half of the total energy consumed is associated with construction of the treatment plant and the sewage collection system. Electrical energy used at the plant accounts for another 30-35% of the total energy usage. The remainder is distributed among energy for production of chemicals, digester heating, building heat, auxiliary fuel for sludge incineration, and fuel for trucks hauling dewatered sludge to the land disposal site. Auxiliary fuel for incineration of sludge represents about 10% of the total energy budget. If dewatered sludge is trucked to land disposal, the energy consumed is usually small compared to energy used for incineration. On the other hand, if liquid sludge is trucked to land disposal, the energy used can be equivalent or even greater than the energy used for incineration.

Energy used to operate the treatment plant includes electrical energy and heat energy for digester heating, building heat, sludge incineration, and hauling of sludge to land disposal. Electrical energy represents 65-75% of the energy used for plant operation. Building heat is estimated at only 5-10% of the operating energy.

Energy can be conserved or recovered within the treatment plant in various ways. For example, energy used for supplying air to the activated sludge process can be reduced significantly by the use of efficient aeration devices and proper maintenance. As much as 80% of the building heat used for ventilating work spaces can be recovered by the use of energy wheels. The anaerobic digestion process produces methane gas which, when used as a fuel for internal combustion engines, can recover about 573 kwh/mg for use in operating the plant. Heat from the water jackets of the internal combustion engines can be used to heat the anaerobic digesters. In very large plants it is also possible to incinerate all of the sludge produced and recover part of the heat of combustion in a waste heat boiler. Steam from the waste heat boiler can then be used in a steam turbine to produce mechanical or electrical energy for use in the plant. The analysis made of this system shows that energy recovery is competitive with anaerobic digestion only in large plants and only when the moisture content of the incinerated sludge is low.

TABLE 1. ESTIMATED TOTAL ENERGY BUDGET FOR MUNICIPAL WASTEWATER TREATMENT PLANTS*

	1 mgd	10 mgd	100 mgd
1. Sewer Construction	1352 (36.4%)	777 (29.4%)	642 (28.0%)
2. Plant Construction	758 (20.4%)	363 (13.7%)	174 (7.6%)
3. Electrical Energy	1100 (29.6%)	893 (33.7%)	835 (36.4%)
4. Chemicals	158 (4.3%)	158 (6.0%)	158 (6.9%)
5. Digester Heating	168 (4.5%)	168 (6.3%)	168 (7.3%)
6. Building Heat	160 (4.3%)	59 (2.2%)	86 (3.8%)
7. Sludge Hauling	20 (0.5%)		
8. Sludge Incineration		230 (8.7%)	230 (10.0%)
Total Energy Consumption	3716	2648	2293

*In terms of kilowatt-hours per million gallons of wastewater treated. Estimates are based on activated sludge plants with anaerobic digestion. Sludge disposal is by incineration in the 10 mgd and 100 mgd sizes and by hauling dewatered sludge 40 miles one-way to land spreading at the 1 mgd size.

TABLE 2. ESTIMATED OPERATING ENERGY BUDGET FOR MUNICIPAL WASTEWATER TREATMENT PLANTS

	1 mgd		10 mgd		100 mgd	
	Used	Recoverable	Used	Recoverable	Used	Recoverable
1. Electrical Energy	1100	573	893	573	835	573
2. Digester Heating	168	152	168	152	168	152
3. Building Heat	160	106	59	39	86	57
4. Sludge Hauling	20					
5. Sludge Incineration			230		230	
	1448	831	1350	764	1319	782

*In terms of kilowatt-hours per million gallons of wastewater treated. Estimates are based on activated sludge plants with anaerobic digestion. Sludge disposal is by incineration at the 10 mgd and 100 mgd sizes and by hauling dewatered sludge 40 miles one-way to land spreading at the 1 mgd size. Energy recovery is by generation of electrical power with IC engine using digester gas as fuel. The waste heat from the IC engines is used to heat the digesters. Energy wheels are utilized to conserve building heat.

SECTION 3

ELECTRICAL ENERGY FOR PLANT OPERATION

Electrical energy is used in wastewater treatment plants for pumping fluids such as water, air, or sludge, and for other mechanical chores. A detailed accounting of electrical energy usage is given in reference 1, but approximate estimates for individual processes are shown in Table 3. Total electrical power consumption is approximately expressed as follows:

$$\text{kwh/mg} = 390\ \text{MGD}^{-0.15} \quad \text{(primary plants)} \tag{1}$$

$$\text{kwh/mg} = 700\ \text{MGD}^{-0.12} \quad \text{(high rate trickling filter plants)} \tag{2}$$

$$\text{kwh/mg} = 1100\ \text{MGD}^{-0.06} \quad \text{(activated sludge plants)} \tag{3}$$

Thus, it can be seen that at the 1 mgd size, the trickling filter plant requires 80% more energy than the primary plant, and the activated sludge plant requires roughly three times the energy of the primary plant. The economy of scale is greatest for the primary plant which at 100 mgd utilizes only one-half the energy per gallon treated used at the 1 mgd size. This ratio between unit energy consumption at 1 mgd and 100 mgd is 1.74 for the trickling filter plant and 1.32 for the activated sludge plant.

In activated sludge plants, about 57% of the electrical energy is consumed in supplying diffused air, about 20% in pumping the influent and return streams, and another 6% for mixing and heating the anaerobic digester. Thus, about 83% of the total electrical energy consumption is associated with three processes. Since the diffused air system appears to offer the greatest potential for conservation of electrical energy, this process will be discussed in greater detail. Adiabatic work for compressing atmospheric air (14.7 psia - 70°F) to gage pressures in the range 6-10 psig can be approximated (within about ½%) by the following linear relationship:

$$\text{Btu/lb} = 2.2 + 1.825\ \text{GP} \tag{4}$$

GP = compressor exit pressure, psig

If the average adiabatic efficiency of the air compressor is taken as 75% and the efficiency of the electric drive motor as 95%, the two coefficients in equation 4 can be divided by 0.7125 to find a relationship for pump work.

TABLE 3. ESTIMATED ELECTRICAL ENERGY CONSUMPTION FOR OPERATION OF MUNICIPAL WASTEWATER TREATMENT PROCESSES: KILOWATT-HOURS PER MILLION GALLONS TREATED FOR THREE PLANT SIZES (mgd = millions of gallons treated/day)

	1 mgd	10 mgd	100 mgd
1. Preliminary Treatment	18.5	6.6	2.5
2. Influent Pumping (30 ft TDH)*	153.0	145.1	129.3
3. Primary Sedimentation	30.6	12.2	7.3
4. Recirculation Pumping			
a. Trickling Filters (Q_r/Q = 3.0)	183.0	174.0	155.2
b. Activated Sludge (Q_r/Q = 0.5)	45.0	42.3	31.3
5. Diffused Air Aeration (AEF = 6%)	532.0	532.0	532.0
6. Mechanical Aeration (2 lb O_2/hp-hr)	404.0	404.0	404.0
7. Final Sedimentation	30.6	12.2	7.3
8. Chlorination	0.7	0.7	2.7
9. Sludge Pumping	2.7	2.7	2.7
10. Gravity Thickening	10.2	2.0	0.4
11. Air Flotation Thickening	70.0	60.8	46.9
12. Anaerobic Digestion	123.6	45.6	19.1
13. Vacuum Filtration	58.5	34.6	36.4
14. Incineration	65.0	28.7	25.9
15. Lights and Misc. Power	57.0	21.0	24.0

*TDH = total dynamic pumping head, Q_r/Q = return flow rate/average daily plant flow rate.
AEF = aeration efficiency in percent for diffused air and lb O_2/hp-hr for mechanical aeration.

For diffused air equipment, aeration efficiency (AEF) is defined as the mass of air dissolved in the aeration basin contents divided by the mass of air supplied to the air diffusers. Aeration efficiency is then expressed as a percentage. Since atmospheric air is 23.2% oxygen by mass and 3413 Btu's are equivalent to one kilowatt-hour, the electrical power consumed in delivering one pound of oxygen can be expressed as a linear function of compressor exit pressure and aeration efficiency as follows:

$$\text{kwh/lb } O_2 = (0.39 + 0.318 \text{ GP})/\text{AEF} \qquad (5)$$

Thus, from equation 5, electrical power consumption for diffused air can be estimated as 0.49 kwh/lb O_2 delivered when the aeration efficiency is 6% and the gage pressure at the compressor exit is 8 psig. It can be seen that electrical power consumption for diffused air is inversely proportional to aeration efficiency and also very dependent on the compressor exit pressure.

The amount of oxygen consumed in the activated sludge process depends on the BOD concentration of primary effluent as well as the operating sludge retention time (SRT). For conventional activated sludge, a rule-of-thumb of one pound of oxygen per pound of BOD entering the process is commonly used. Thus, if the BOD concentration of primary effluent is 130 mg/l, the oxygen consumed in the process can be estimated as about 1083 lb O_2/mg. If 0.49 kwh/lb O_2 is used for compressing the air, the power consumption can therefore be estimated at about 531 kwh/mg. This is roughly equivalent to 1 scf per gallon of water treated which is another commonly used rule-of-thumb. A more detailed discussion of oxygen consumption is given on pages 12 and 13.

Although the field efficiency of mechanical aerators varies with the size of the aerator drive motor and the spatial relationship between the aeration basin and the rotor of the mechanical aerator, a generally accepted average value for efficiency is 2.0 lb O_2/hp-hr or 2.68 lb O_2/kwh. Thus, electrical power consumption for mechanical aerators can be estimated at about 0.37 kwh/lb O_2 delivered or about 404 kwh/mg, using the assumptions mentioned above. It can be seen from equation 2 that when the compressor exit pressure is 8 psig, a diffused air system will consume the same amount of electrical power as a mechanical aerator system when the aeration efficiency is 7.87%.

Three principal methods are available for conserving electrical energy used for aeration; first choosing the most efficient aeration equipment and providing the necessary maintenance; second, providing for automatic control of the dissolved oxygen concentration in the aeration basin; and third, operating the process at a sludge retention time which maximizes sludge production and minimizes oxygen demand.

The importance of selecting efficient aeration equipment and providing adequate maintenance was demonstrated in an important set of experiments conducted at the Jones Island Treatment Plant in Milwaukee, Wisconsin by

Leary, Ernest, and Katz (3-4). Aeration efficiency of various kinds of aeration equipment was measured under operating conditions.

The method used was to collect samples of the gas discharged from the water surface. From the volume of the gas and the nitrogen content of the gas, the amount of air supplied per unit of water surface was computed. This was checked against the measured mass of air supplied. From the oxygen content of the gas, the aeration efficiency was calculated. The carbon dioxide concentration in the off-gas was used as a check. The experiments were performed on the East Plant which is designed to treat 115 mgd of wastewater. Each aerator was designed for a two-pass flow, and each pass had a length of 370 ft, a width of 22 ft, and a depth of 15 ft.

When the experimental work started, the East Plant was equipped with ceramic tube diffusers which were placed on spiral flow. The field efficiency in 1962 was measured as 5.4%, but this dropped to 3.2% in 1963 and then increased to 5.1% in 1964 as a result of a program of cleaning and refurbishing the diffusers.

During the same period, the 85 mgd West Plant was operated with an average oxygen consumption of 0.8 lb O_2/lb BOD removed. The West Plant is equipped with ridge and furrow aerators distributed uniformly along the bottom of the aerator. The aeration efficiency of the ridge and furror diffusers was measured in 1961 as 10.7%, and this decreased to 7.9% in 1962. By cleaning and refurbishing the diffusers, the aeration efficiency was increased to 14.2%, as measured in the 1964 measurements. These experiments show dramatically the conservation of electrical power which can be achieved by the use of efficient aeration equipment and proper maintenance policies.

In municipal wastewater treatment plants, the production of wastewater varies in volume and strength in a reasonably predictable diurnal pattern. Thus, the demand for oxygen also varies an dissolved oxygen probes installed in the aeration basin can be used to match the oxygen supplied to the process with the demand. When diffused air is used, the amount of air supplied must be modulated by control of a valve on the compressor inlet. When mechanical aerators are used, the oxygen supplied is controlled by varying the submergence of the rotor blades by means of variables weirs. Dissolved oxygen control has been demonstrated in hundreds of plants and can cut the power consumption (5-6) by approximately 20%.

The amount of oxygen used in the activated sludge process is known to depend on the amount of BOD synthesized to microorganisms and the amount of sludge destroyed in the process by endogenous respiration. This can be seen by recognizing that the mass of COD removed in the process must equal the mass of oxygen consumed in the process. For example, if one pound of BOD, equivalent to 1.5 lb of COD, is synthesized to 0.65 lb of microorganisms having a COD equivalent of 1.42 lb COD/lb microorganisms, the net COD removal will be 1.5 - (0.65 x 1.42) or 0.58 lb COD. Thus, when the synthesized microorganisms are removed from the process, at once the oxygen usage will be 0.58 lb O_2/lb BOD removed. If the microorganisms remain in the process to be destroyed by endogenous respiration, the mass of microorganisms wasted from the process will be reduced by a maximum of 81% of their original mass when the sludge retention time (SRT) is very long. Sludge retention time (days) is defined as the mass (lb) of microorganisms held in the process divided by the rate at which they are wasted from the process (lb per day). Thus, at very long SRT values, the oxygen consumption can be as much as 1.5 - (0.19 x 0.65 x 1.42) or about 1.3 lb O_2/lb BOD removed. If the endogenous respiration rate is estimated at 12.5% per day, the theoretical relationship between oxygen consumption and SRT can be written as follows:

$$\text{lb } O_2/\text{lb BOD removed} = 0.58 + 0.0935/(0.125 + 1/\text{SRT})$$

Since operating SRT values normally range from 1-10 days with about 5 days correlating to the conventional activated sludge process, it can be seen that oxygen usage will vary from about 0.66 lb O_2/lb BOD removed at a 1-day SRT to about 1.0 lb O_2/lb BOD removed at a 10-day SRT. Oxygen usage at the 5-day SRT will be about 0.87 lb O_2/lb BOD removed. Therefore, use of the short detention time "modified" activated sludge process (1-day SRT) can be expected to utilize about 25% less oxygen than the conventional 5-day SRT process.

To summarize, a reduction of 50% in electrical power consumption for supplying diffused air to the activated sludge process is not an unreasonable goal. This would correlate to a reduction of about 30% in total electrical energy usage at the plant.

SECTION 4

ENERGY FOR PLANT AND SEWER CONSTRUCTION

Energy consumed in construction of treatment plants and collection sewers for municipal wastewater represents a significant fraction of the total energy budget. The most widely used reference for estimating energy used in construction is the input-output analysis performed at the Center for Advanced Computation of the University of Illinois. The most recent report is CAC Document No. 140 (7) which estimates energy consumed in New Public Utilities Construction as 86,929 Btu/1963 construction dollar. In 1963, construction cost for a 1 mgd activated sludge treatment plant was about $500,000. Thus, energy for construction would be estimated as 43.5 billion Btu. If construction energy is allocated per volumetric unit of water treated and the useful life of the plant is taken as 20 years, the construction energy can be expressed as 6 million Btu/mg or 567 kwh/mg, assuming 10,500 Btu/kwh. Since electrical power consumption in a 1 mgd activated sludge plant has been estimated at about 1100 kwh/mg (1), it can be seen that plant construction energy is roughly one-half the electrical energy used in operating the plant.

The energy consumed in plant and sewer construction can also be estimated by summing the energy used in the manufacture of the materials and the energy used for on-site work such as excavation. A pamphlet (8) entitled "Sewer and Sewage Treatment Plant Construction Cost Index," published by FWPCA, gives the rationale for development of the EPA plant and sewer indexes. This pamphlet also contains a detailed breakdown of the materials and labor components for construction of a 1 mgd trickling filter plant and a one million dollar sewer project involving the laying of 35,000 ft of sewer. This information was used together with estimates of energy for the manufacture of building materials to make estimates of energy consumed in building sewers and plants. Estimates of energy utilized for the manufacture of building materials, taken from references (9) and (10), are shown in Table 4. Table 5 shows a computation of the energy consumed in constructing a 1 mgd trickling filter plant. Table 6 shows a similar computation for the energy consumed in constructing 35,000 ft of sewer. The cost of constructing the 1 mgd trickling filter plant was given as $470,000 in 1963 dollars. Therefore, the energy consumption was 124,000 Btu per 1963 dollar. Similarly, the cost of the sewer project for laying 35,000 ft of sewer was 1.03 million dollars in 1963 and the corresponding energy consumption was 42,000 Btu/1963 dollar. These estimates agree reasonably well with the 86,929 Btu/1963 dollar given in the CAC report.

TABLE 4. ENERGY CONSUMPTION FOR PRODUCTION OF BUILDING MATERIALS

1. Iron and Steel Shipped: 31 million Btu/ton
2. Cement Production: 1.22 million Btu/bbl
3. Concrete: 500 lb. cement/cu. yd. = 1.33 bbl/cu. yd.

   Ready Mix = 0.272 million Btu/cu. yd.

   1.22 x 1.33 + 0.272 = 1.89 million Btu/cu. yd.
4. Brick: 8000 Btu/brick (7.5" x 3.5" x 2.25")
5. Vitrified Clay Pipe: 5100 Btu/lb
6. Lime: 3770 Btu/lb.
7. Glass: 17 million Btu/ton
8. Forging: 35 million Btu/ton
9. Foundry: 13 million Btu/ton
10. Die Casting: 12,000 Btu/lb.
11. Rubber: 13,000 Btu/lb.
12. Industrial Chemicals: 6240 Btu/lb.
13. Petroleum Products: 590,000 Btu/bbl

TABLE 5. ITEMIZED ENERGY CONSUMED IN CONSTRUCTION OF 1 mgd TRICKLING FILTER WASTEWATER TREATMENT PLANT IN TERMS OF Btu's AND EQUIVALENT ELECTRICAL ENERGY IN KILOWATT-HOURS

1.	Total Iron and Steel: 1688 tons @ 31 million Btu/ton	52.3 billion Btu	4.98 million kw-hr
2.	Ready Mix Concrete: 1794 cu. yd. @ 1.89 million Btu/cu. yd.	3.4 billion Btu	0.32 million kw-hr
3.	Vitrified Clay Pipe: 748 ft. - 126.8 ton @ 5100 Btu/lb.	1.3 billion Btu	0.12 million kw-hr
4.	Concrete Pipe: 1952 ft. - 434.3 ton @ 422 Btu/lb.	0.4 billion Btu	0.04 million kw-hr
5.	Concrete Block: 9884 - 30 lb ea. @ 422 Btu/lb.	0.1 billion Btu	0.01 million kw-hr
6.	Brick: 62,000 @ 8000 Btu/brick	0.5 billion Btu	0.05 million kw-hr
7.	Excavation & Backfill: 3500 cu. yd. @ 15,000 Btu/cu. yd.	.05 billion Btu	.05 million kw-hr
	Total Energy for Treatment Plant Construction	58.05 billion Btu	5.53 million kw-hr

TABLE 6. ITEMIZED ENERGY CONSUMED IN CONSTRUCTION OF 35,000 FT. (6.652 MILES) OF MUNICIPAL SEWER IN TERMS OF Btu's AND EQUIVALENT ELECTRICAL ENERGY IN KILOWATT-HOURS

1.	Total Iron and Steel: 1067 tons @ 31 million Btu/ton	33.1 billion Btu	3.15 million kw-hr
2.	Ready Mix Concrete: 2632 Cu. yr. @ 1.89 million Btu/cu.yd	5.0 billion Btu	0.47 million kw-hr
3.	Fuel Usage: 13,950 equip. hrs. @ 150,000 Btu/hr.	2.1 billion Btu	0.20 million kw-hr
4.	Vitrified Clay Pipe: 10,414 ft. - 32 lb/ft @ 5100 Btu/lb	1.7 billion Btu	0.16 million kw-hr
5.	Concrete Pipe: 25,000 ft. - 66 lb/ft @ 422 Btu/lb	0.7 billion Btu	0.07 million kw-hr
6.	Concrete Brick: 76,000 ft. - 5.9 lb. ea. @ 422 Btu/lb	0.2 billion Btu	0.02 million kw-hr
7.	Concrete Block: 6800 - 30 lb. ea. @ 422 Btu/lb	0.1 billion Btu	0.01 million kw-hr
	Total Energy for Sewer Construction	42.9 billion Btu	4.08 million kw-hr

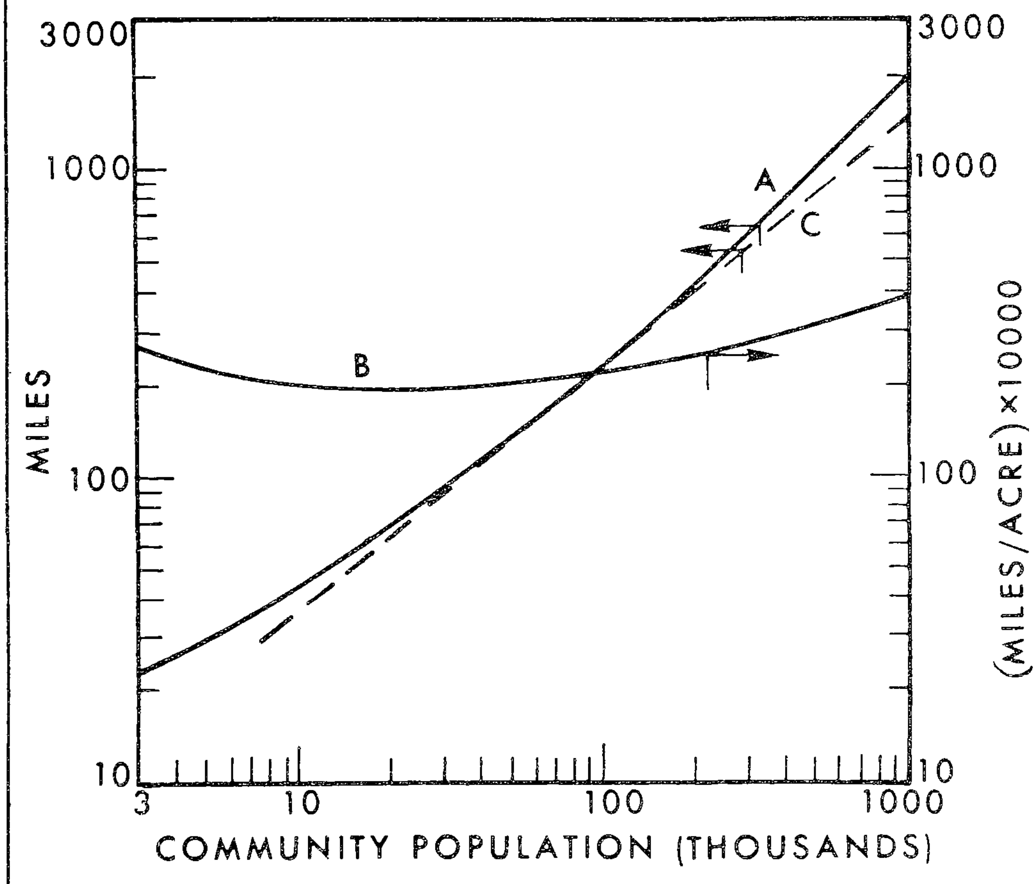

Figure 1. Relationship between community size and (A) total miles of street: (B) street (sewer) miles per 10,000 acres; and (C) total miles of sewer.

The cost of constructing plants increases with plant size at a slope on log-log paper of about 0.65-0.7. Thus, the cost of energy consumed in building plants might be expressed as follows:

$$\text{Energy Consumption, billions of Btu} = 58.1\ \text{MGD}^{0.68} \qquad (6)$$

Energy consumed in the construction of sewers is more likely to be directly proportional to the length of the sewer. A relationship for estimating the length of sewer as a function of community population (11) is shown by the dashed line (C) in Figure 1. Estimates of the length of street as a function of community size are also shown in Figure 1 by the solid line (A). It can be seen that these relationships are similar, but the street length is probably more reliable as an estimate of sewer length. Therefore, if a population of 10,000 is taken as equivalent to 1 mgd of municipal wastewater volume flow, a 1 mgd plant will be served by about 40 miles of sewer, a 10 mgd plant by 230 miles, and a 100 mgd plant by about 1900 miles.

If the energy for laying sewers is taken as 42.9 million Btu/35,000 ft or 1.226 million Btu/ft (6.46 billion Btu/mile), it can be seen that for a community of 10,000 persons (1 mgd), the energy for construction will be 259 billion Btu for the sewer and 58.1 billion Btu for the plant, making a total of 317 billion Btu or 30.2 million kwh. If the useful life of the sewer is taken as 50 years (18,250 days) and the useful life of the plant as 20 years (7300 days), the energy consumption per day will be 1352 kwh/mg (10,500 Btu/kwh) for the sewer and 758 kwh/mg for the plant, making a total of 2110 kwh/mg.

Since the electrical power consumed in a 1 mgd activated sludge plant has been estimated at 1100 kwh/mg, it follows that the energy consumed in constructing the plant and sewer system is roughly twice the electrical energy used.

For the 10 mgd plant with 230 miles of sewer, the energy consumed for constructing sewers will be 7766 kwh/day or 777 kwh/mg. Similarly, the energy used for constructing the plant will be 3628 kwh/day or 363 kwh/mg. The total for the 10 mgd plant is, therefore, 1140 kwh/mg or about 128% of the 893 kwh/mg electrical energy used at the plant.

For the 100 mgd plant with 1900 miles of sewer, the energy for constructing sewers will be 642 kwh/mg and the energy for constructing the plant will be 174 kwh/mg, for a total of 816 kwh/mg or roughly the same as the 835 kwh/mg daily electrical energy used at the plant.

SECTION 5

ENERGY FOR MANUFACTURE OF PROCESS CHEMICALS

Energy consumed in the production of chemicals can represent a significant fraction of the total energy used in the treatment of municipal wastewater. Estimates available in literature differ for a number of reasons. For example, production processes used often produce not one but two or more chemicals, raising the question of how the production energy should be apportioned between the products. Also, some processes such as that used for production of sulfuric acid naturally produce rather than consume heat. This heat energy, under the proper circumstances, can be recovered for other uses. These problems will be considered in the following discussion for individual chemicals. Some chemical producing processes, such as that for lime, use primarily heat energy while others, such as that used for production of chlorine, use primarily electrical energy. A conversion factor of 10,500 Btu/kwh will be used here. This value is a commonly used average conversion factor used for coal fired steam power plants or stationary diesel engines.

The Department of Commerce and the Department of Energy are conducting a voluntary industrial energy program (9) which contains some of the best estimates for overall energy used in the production of various manufactured products. The National Lime Association reports that in 1975 an average of 3770 Btu were consumed for the production of each pound of lime. This is equivalent to 0.36 kwh/lb of lime.

The electrolytic process for producing chlorine from sodium chloride also produces caustic soda (NaOH). A small amount of additional energy is required for concentrating the caustic soda solution. The Ford Foundation report (10) estimates the total energy used in producing chlorine and caustic soda as 2.216 kwh/lb of total product. Since the products are roughly 47% chlorine and 43% caustic soda, a reasonable estimate for chlorine production is 1.04 kwh/lb of chlorine. In a report written for the Canadian Ministry of the Environment, Zarnett (12) took a similar approach in working with the estimates provided by Shreve (13) and estimated 1.21 kwh/lb of chlorine produced. The IR&T report (14) on energy use by various industrial chemicals showed that in 1971 energy used in the alkalies and chlorine industry averaged 2.05 kwh/lb. The corresponding value for 1973 was 1.98 kwh/lb. Data from Diamond Shamrock on the efficiency of their Sanilec system for in-plant production of chlorine shows that chlorine can be produced for 2 kwh/lb under ideal conditions. Thus, the consumption of energy for production of chlorine ranges from 1-2 kwh/lb, depending on the assumptions made.

Dry alum (17.1% Al_2O_3) is made by mixing aluminum ore (Bauxite) with sulfuric acid. Heat is required to concentrate the clarified aluminum sulfate solution in open steam-heated evaporators. Shreve (13) estimated that 640 lb of coal and 29 kwh are needed to produce one ton of alum. Using 11,790 Btu/lb of coal, Zarnett (12) computed 7.85 million Btu/ton of alum. This is equivalent to 0.374 kwh/lb of alum. The energy required to produce the sulfuric acid (1140 lb/ton of alum) is negligible as will be shown later.

Ferric chloride is produced by treating spent pickling liquor with chlorine. When sulfuric or hydrochloric acid is used to clean steel, the spent solutions are primarily ferrous chloride ($FeCl_2$) or ferrous sulfate ($FeSO_4$). Since the effectiveness of either iron salt is dependent on the amount of ferric iron present, the stoichiometric amount of chlorine needed to oxidize ferrous iron to ferric iron is best expressed as 0.635 lb chlorine/lb iron. Thus, whether the pickling liquor is ferrous chloride or ferrous sulfate, the amount of chlorine used is 0.635 times 0.3443 lb iron per lb of equivalent ferric chloride or 0.22 lb chlorine per lb of equivalent ferric chloride. If the energy for production of chlorine is taken as 2 kwh/lb chlorine, the energy for production of ferric chloride or its equivalent ferrous sulfate is 0.44 kwh/lb.

Pure oxygen can be produced at the plant site by the cryogenic process or by pressure swing adsorption (PSA). The commercial separation of oxygen from atmospheric air has large amounts of nitrogen gas as a by-product. The Ford Foundation report (10) estimated the energy used for production of oxygen as 19 kwh/1000 cu. ft., in terms of 1958 technology. This is equivalent to 0.23 kwh/lb. Culp/Wesner/Culp (2) interviewed a number of oxygen generation equipment suppliers and averaged their estimates to 0.25 kwh/lb. An EPA in-house study (15) estimated the power consumption for generation as 0.23 kwh/lb for PSA generation and 0.133 kwh/lb for cryogenic generation. However, a significant amount of energy is also needed for dissolving the oxygen in the activated sludge aeration basin. The total energy consumption for generation and dissolution was estimated as 0.382 kwh/lb for PSA and 0.271 kwh/lb for cryogenic.

Total energy for production of methanol which includes the energy of the feedstock (natural gas) was estimated by IR&T to be 18,500 Btu/lb in 1971 and 17,890 Btu/lb in 1973. This averages to 18,200 Btu/lb or 1.73 kwh/lb. The C/W/C report (2) estimates the energy for production of methanol as 0.7-1.4 kwh/lb.

The best estimates of energy consumption in the production of activated carbon are given in a paper by Bernardin and Petura (16) of the Calgon Corporation. They estimate energy for the manufacture of 51,200 Btu/lb of activated carbon. This estimate includes the Btu content of the coal used as feedstock. Energy for reactivation of spent carbon was estimated as 4260 Btu/lb or about 8.3% of the energy required for manufacture of the carbon. Manufacturing energy is equivalent to 4.88 kwh/lb and reactivation is equivalent to 0.41 kwh/lb.

As mentioned earlier, the production of sulfuric acid involves the burning of sulfur which produces about 2.6 million Btu or 1.1 tons of high pressure steam per ton of sulfuric acid produced. The electrical energy consumed is only about 9 kwh/ton of sulfuric acid produced. These data are from the Sulfur Institute Technical Bulletin No. 8. It can be concluded from this that the energy consumed in producing sulfuric acid is negligible.

If dewatering chemicals are estimated as 200 lb of lime and 150 lb of ferric chloride per ton of dry sludge solids, the off-site energy used for production of the chemicals will be about 91 kwh/mg. If the final effluent stream is chlorinated at a concentration of 8 mg/l and the cost of producing chlorine is taken as one kwh/lb of chlorine, an additional expenditure of 67 kwh/mg will be incurred, making a total of 158 kwh/mg for off-site production of chemicals.

SECTION 6

HEAT ENERGY USED AT THE PLANT

Anaerobic Digester Heating:

Heat energy is used in the plant for holding the contents of the anaerobic digester at 95°F, for heating the space used for housing equipment and personnel, and for sludge incineration.

Heat energy is utilized in the anaerobic digester for raising the temperature of the sludge stream up to the operating temperature of the digester and also for overcoming the loss of heat through the digester walls. If the difference between the digester operating temperature and the ambient temperature of the sludge stream is called DT in °F, the sludge production rate in lb sludge solids produced mg of water treated is called W, and the concentration of solids in the sludge feed stream is TSS in percent, the amount of heat used to raise the sludge temperature can be computed as follows:

$$Btu/mg = 100 \cdot W \cdot DT/TSS \qquad (7)$$

Heat loss through the digester walls can be computed using a rule-of-thumb given in the WPCF Manual of Practice No. 8 (17) which states that in the northern part of the U.S., daily heat losses can be estimated as 62,500 Btu/1000 cu. ft. of digester volume. This estimate can be adjusted for climatic conditions by multiplying by a factor (F) of 0.5 for digesters in middle U.S. and by a factor of 0.3 in southern U.S. Primary digesters are normally heated while secondary digesters are not. If the hydraulic retention time (HRT) for the primary digester is estimated at 15 days, the heat loss through the walls in northern U.S. locations can be expressed as follows:

$$Btu/mg = 100 \cdot W \cdot HRT \cdot F/TSS \qquad (8)$$

HRT = hydraulic retention time, days

F = factor to account for geographical location

These two relationships can be added to find the total heat energy used by anaerobic digesters as follows:

$$Btu/mg = (100 \cdot W/TSS)(DT + HRT \cdot F) \quad (9)$$

The temperature of the digester feed stream will also depend on the climate at the plant. For example, the temperature of wastewater averages 58°F at Buffalo, NY, 60°F at Chicago, IL, 63°F at Richmond, IN, 62°F at Minneapolis-St. Paul, and 51°F at Ely, Minnesota. Therefore, conservative estimates for sludge temperature might be about 58°F for northern U.S., 63°F for middle U.S., and about 68°F for southern U.S. Sludge production in secondary plants averages about 2000 lb solids/mg, and the concentration of thickened combined sludge can be estimated at about 4.5%. Therefore, if the hydraulic retention time of the primary digester is 15 days, the total heat consumption for anaerobic digesters will be about 2.3 million Btu/mg for northern U.S., 1.76 million Btu/mg for middle U.S., and 1.4 million Btu/mg for southern U.S. Using the conversion factor of 10,500 Btu/kwh, these estimates are equivalent to 219 kwh/mg, 168 kwh/mg, and 133 kwh/mg. Equation (9) shows that these estimates are directly proportional to the sludge production and inversely proportional to the sludge concentration of the feed stream. For example, if the concentration of the sludge was 3% instead of 4.5%, which might be the case without thickening, the estimates would be increased by a factor of 1.5.

Space Heating:

Heating requirements for habitable space in wastewater treatment plants is easily computed when a specific plant, for which all construction details is known, is considered. Making estimates for plants in general is much more difficult. Information of this kind was compiled by Voegtle (18) from data for 10-12 plants. Voegtle's estimates are shown by the horizontal solid lines in Figure 2. Smith (1) estimated electrical energy consumption in activated sludge plants to be about 900 kwh/mg. Voegtle's estimates for space heating can be seen to be about 12 billion Btu/yr at 10 mgd or about 250 billion Btu/yr at 100 mgd. Using the conversion of 10,500 Btu, Voegtle's estimates correlate to 313 kwh/mg at 10 mgd and 752 kwh/mg at 100 mgd. Thus, according to Voegtle, building heat requirements are a significant fraction of the electrical power requirements. Because of the apparent importance of space heating requirements, an independent study was made based on information gathered from operating plants.

Estimates of heat consumed for space heating from ten plants are shown by the data points in Figure 2. The squared point represents the Ely, Minnesota plant which is atypical because the plant includes two-stage lime clarification, tertiary filters, and vacuum filters for dewatering of all sludges. Since all tertiary processes are housed, the space to be heated at Ely is also atypical. It can be seen from Figure 2 that two of the points fall within the range estimated by Voegtle, but the majority of the points suggest that Voegtle's estimates are high. A tabulation of the data gathered is shown in Table 7. Since the heat consumed for space heating clearly depends on the volume of the space heated, as well as the climate at the plant site, an effort was made to relate heat consumed to these variables.

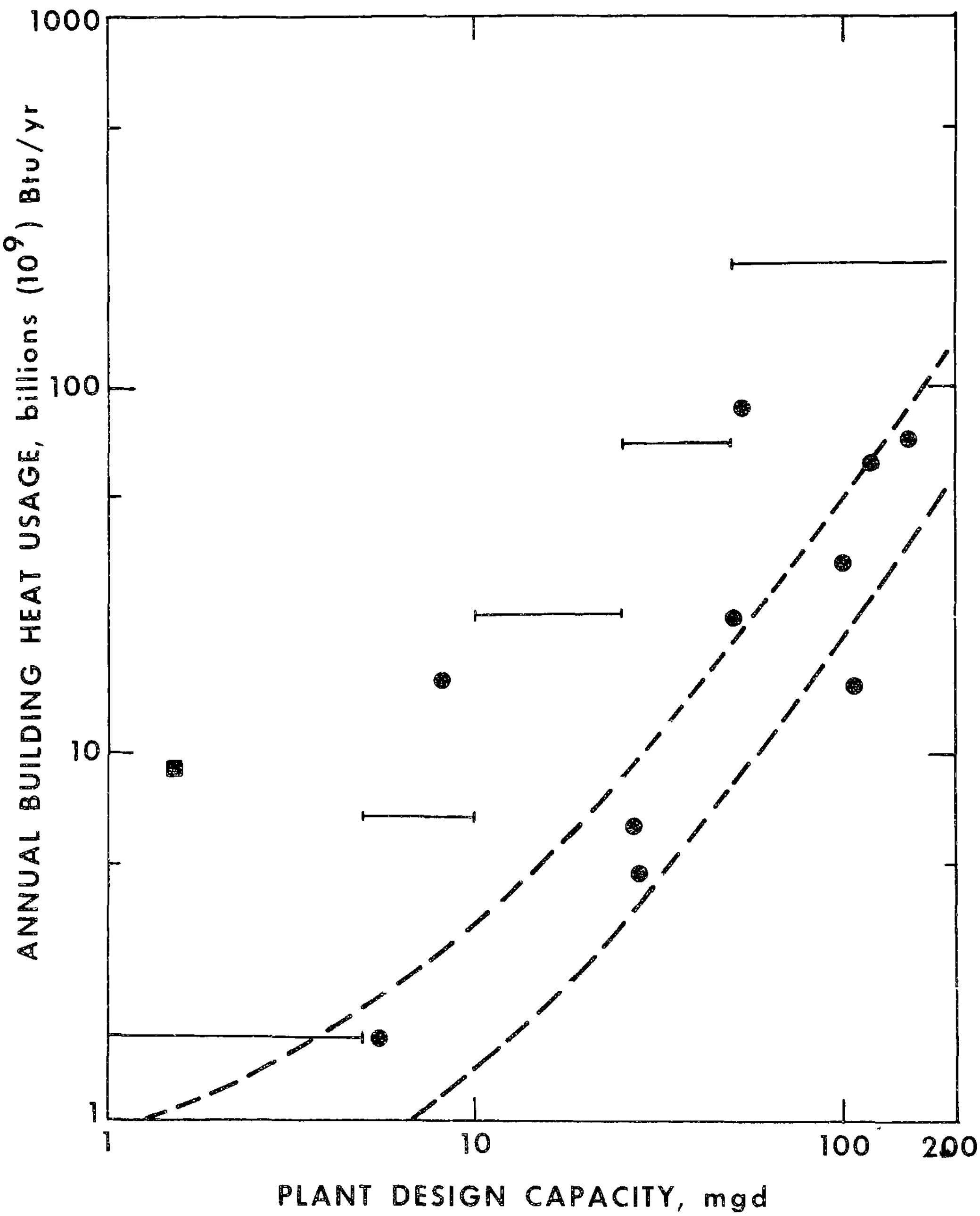

Figure 2. Space heating requirements for wastewater treatment plants versus plant size. Solid lines represent estimates by Voegtle, circled points are typical plant data, squared point represents Ely, Minnesota tertiary plant, dashed lines show estimates based on building volume and 4 Btu/yr per cu ft per annual degree-days.

TABLE 7. ESTIMATES OF HEATED VOLUME AND HEAT USED FOR SPACE HEATING IN WASTEWATER TREATMENT PLANTS

	State	Plant Size	Degree-days/yr	Heated Volume, Million cu ft	Annual Heat Load billion Btu/yr	Btu/yr per cu ft per degree-day
1.	New York	150 mgd	7218	2.713	71.65	3.65
2.	Ohio	100 mgd	6144		33.2	
3.	Ohio	8 mgd	5522	0.694	16.0	4.18
4.	Ohio	28 mgd	5522		4.75	
5.	Virginia	27 mgd	3818	0.40	6.42	4.20
6.	Ohio	51	5522		23.5	
7.	Ohio	120 mgd	6525		62.0	
8.	Ohio	109 mgd	5522	1.68	15.2	1.64
9.	Wisconsin	5.5 mgd	7536		1.7	
10.	Minnesota	1.5 mgd			9.6	
11.	Wisconsin	54 mgd			88.6	

In wastewater treatment plants, the principal loss of building heat is associated with the ventilation requirements. For example, the Ten State Standards (19) recommends one complete air change per minute for chlorination housing, twelve complete air changes per hour for wet wells, and six air changes per hour for tunnels and dry wells. Current practice is to provide about six air changes per hour for enclosed sludge handling facilities. The C/W/C report (2) estimated the ventilation and infiltration requirements for the total composite building volume at 5.5 air changes per hour. This estimate appears to represent reasonably well the observed heat loss in operating plants. Heat loss through walls and ceilings is small compared to the heat loss from ventilation; roughly 20% of the ventilation heat loss. The ventilation heat loss can be readily calculated as follows: Ventilation heat loss, Btu/yr = V x 0.075 x 5.5 x 24 x 0.24 x ^{o}days/0.7. In this equation, V is the building volume ventilated in cubic feet, 0.075 is the density of air (lb/cu ft), 5.5 is the number of air changes per hour, 24 is the number of hours/day, 0.24 is the specific heat of air (Btu/lb/^{o}F), utilization efficiency is 0.7, and ^{o}days is the number of degree-days per year at the site of the building. Thus, with these assumptions, the heat consumption for ventilation at 5.5 air changes/hr can be expressed as 3.394 Btu/yr per degree-day per cu. ft. of volume ventilated. This is shown by the horizontal line in Figure 3.

Heat loss through the walls and ceiling of the building space is more difficult to estimate. ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) Standard 90-75 (20) gives recommended standards for heat loss coefficients for walls (U_w) and ceilings (U_c) in terms of Btu per hour per sq. ft. per degree F. The value of U_w for non-residential buildings is given by the following relationship:

$$U_w = 0.39 - 0.019(^{o}\text{days}/1000) \qquad (10)$$

The corresponding relationship for heat loss through ceiling and roofs is given by the following relationship:

$$U_c = 0.124 - 0.008(^{o}\text{days}/1000) \qquad (11)$$

If the buildings are assumed to be 20 ft high and 40 ft wide, the heat loss through walls and roofs can be expressed as follows:

$$(\text{Btu/yr})/\text{cu ft}/^{o}\text{day} = 24(U_w + U_c)/20 + (1600/V)U_w\ 24 \qquad (12)$$

The second term approaches zero as the building volume becomes large. The total heat loss is shown graphically by the two sloping lines in Figure 3. The lower line is for very large (1,000,000 cu. ft.) buildings and the upper line is for 30,000 cu. ft. which is characteristic of a 1 mgd plant. The four points shown in Figure 3 are reported heat consumption values.

The best way to estimate space heating requirements for wastewater treatment plants appears to be in terms of (Btu/yr)/cu ft/(^{o}days/yr). An average value for the three upper points in Figure 2 is about 4 Btu/yr per

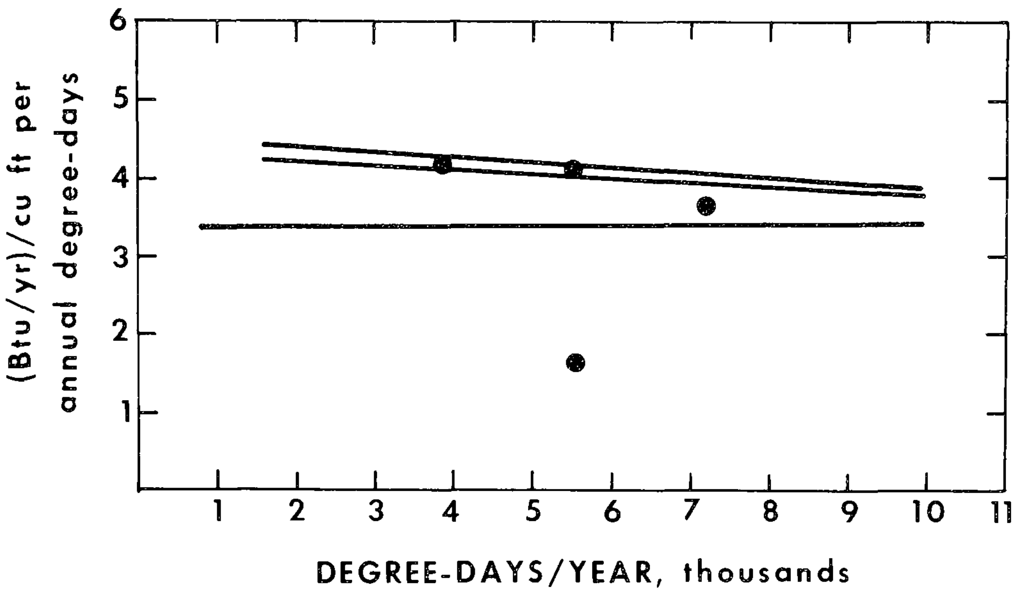

Figure 3. Normalized space heating requirements for wastewater treatment plants in terms of Btu/yr per cu ft of heated space per annual degree-days versus thousands of annual degree-days.

cu ft per annual degree-days. The Federal Housing Administration set a standard of 2 Btu/yr per cu ft per annual degree-days in 1965. Property standards required by the HUD Operation Breakthrough reduced this figure to 1.5 in 1970, and in 1972 FHA set their minimum standard for housing at 1 Btu/yr cu ft per annual degree-days. Thus, as might be expected, the observed heating requirement for wastewater treatment plants is significantly above conventional housing standards. This is undoubtedly due to the requirement for adequate ventilation.

The volume of heated space in wastewater treatment plants can vary widely, depending on the services provided at the plant. In Figure 4, the three squared points are estimates made by George S. Russel of the consulting firm of Russel and Axon in Daytona Beach, Florida, for Cornell University in 1960. The circled points depict recently gathered data from plants considered to be typical. The triangular point represents the Ely, Minnesota tertiary plant. The solid line in Figure 4 can be used as a rough estimate of the amount of heated space to be found in secondary treatment plants.

Thus, if the heat requirement is taken as 4 Btu/yr per cu ft per annual degree-days, an estimate can be found for building heat requirements. The annual degree-days ranges from 3000-8000 for most of the United States. These limits were used together with the estimate of 4 Btu/yr per cu ft per annual degree-days and the estimate of heated volume shown in Figure 4 to find the dashed lines shown in Figure 2. It can be seen that the band enclosed by the dashed lines is a fair representation of the data points and can, therefore, be used as a reasonable estimate for building heat requirements.

The conclusion that a major fraction of the heat used for space heating is associated with heating ventilating air makes the use of energy wheels a potentially attractive device for conservation of energy. The energy wheel, as described by Pallio (21), is an air-to-air heat exchanger which picks up heat from contaminated air being exhausted from the building and transfers it to the fresh outside air being drawn into the building for ventilation. Pallio estimates the efficiency of the energy wheel at 80%.

Heat Pumps:

Heat pumps are being installed in some wastewater treatment plants (21) to remove heat from the final effluent stream and deliver it at a higher temperature (above 100°F) for heating building space. The performance of heat pumps is expressed as the coefficient of performance (COP) which is defined as the amount of heat removed from the wastewater stream divided by the heat equivalent (1 kwh = 3413 Btu) of the electrical power consumed. The COP normally ranges from 2 to 3, depending on the temperature of the wastewater stream. The ASHRAE standard (20) for COP of heat pumps with a water source at 60°F is 2.2. The alternative to using heat pumps is to burn the fuel at the plant site and produce hot water for heating building space. The overall efficiency of a hot water boiler is about 60%. Therefore, if 10,500 Btu of fuel energy is supplied to the boiler, about 6300 Btu will be delivered for heating. If this same fuel is burned in the electrical power generating

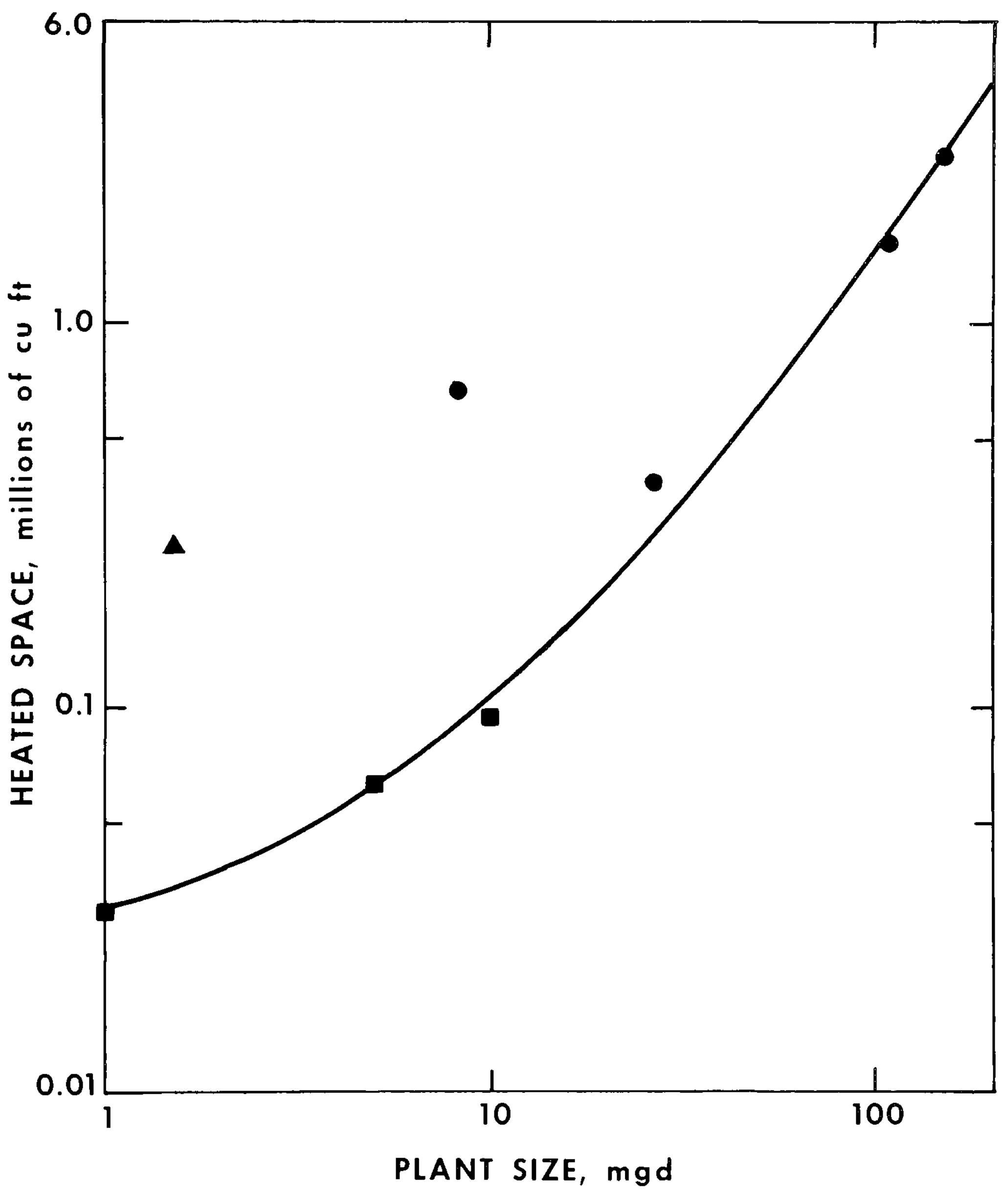

Figure 4. Heated space in wastewater treatment plants versus plant size. Circled points are typical secondary plants, squared points are estimates by George S. Russell, triangular point is Ely, Minnesota tertiary plant.

station, one kwh of electrical energy will be recovered and this will produce 7500 Btu of heat for heating building space when the COP is 2.2. Thus, it can be seen that the energy efficiency provided by heat pumps that use the wastewater effluent stream as a source is not dramatic. The heat pump, however, does have the added advantage of being able to cool as well as heat the building space.

Auxiliary Fuel for Sludge Incineration:

The amount of auxiliary fuel used for sludge incineration can vary widely depending on factors such as the water content of the sludge, the flue gas temperature, and the thermal cycling requirements. The higher heat value for volatile sludge solids varies from 7000-14,000 Btu/lb of dry volatile solids (DVS) with about 10,000 Btu/lb DVS as the average. Heat losses from the operating incinerator include radiation and convection losses, enthalpy of the products of combustion and water content of the sludge, cooling air loss, heat for conversion of dewatering chemicals, and heat loss in the ash. When the sum of the losses is greater than the heat value of the volatile sludge solids, auxiliary fuel is required. Thus, the the amount of auxiliary fuel needed for operation can be calculated (22) when the operating conditions are known.

Most of the heat lost from the incinerator is in the flue gas stream. Flue gases are composed of the vaporized water content of the sludge and the DVS products of combustion. If the fraction of dry solids in the sludge is F_s and the fraction of dry solids which are volatile is F_v, the pounds of water per pound of DVS (W_s) can be calculated as $(1-F_s)/(F_sF_v)$. The enthalpy of water vapor (above 60^oF) can be represented with little error by the following relationship:

$$\text{Btu/lb } H_2O = 1160 + 0.505(T_s-300) \qquad (13)$$

T_s = flue gas set point temperature, ^oF

Thus, it can be seen that if the solids content of the sludge is 25% and the solids are 70% volatile, about 4.3 lb of water is associated with each lb of DVS, and the enthalpy loss in 800^oF flue gases will be 6054 Btu/lb DVS for evaporating the water content of the sludge.

If the chemical composition of the DVS is 56% carbon, 8% hydrogen, 30% oxygen, 5% nitrogen, and 1% sulfur, the enthalpy of the combustion products (above 60^oF) can be estimated by the following relationship:

$$\text{Btu/lb DVS} = (1300 + 450\, E_x) + (2.55 + 2.09\, E_x)(T_s-300) \qquad (14)$$

E_x = excess air supplied/stoichiometric amount

The amount of excess air is adjusted to hold the flue gas temperature (T_s) at some set point. Therefore, a value for E_x can only be found from a mass balance around the incinerator. For example, if the minor losses for radiation and convection, cooling air, conversion of chemicals, and ash are subtracted from the heat value of the DVS, a net heat available is found. If the heat needed to evaporate the water content of the sludge is subtracted from the net heat available, the heat available for combustion products (H_a) can be found. This value can then be set equal to equation (14) and E_x solved for. A minimum recommended value for E_x is 0.5. Therefore, if the value found for E_x is less than 0.5, auxiliary fuel must be added.

If dewatering chemicals consist of 10% lime and 7.5% ferric chloride, the heat used for conversion of the chemicals is about 240 Btu/lb DVS. When 30% of the cooling air is discharged to the atmosphere, about 190 Btu/lb DVS is lost. About 46 Btu/lb DVS is lost in the ash. Estimates for radiation and convection losses vary with the manufacturer, but an average value in terms of Btu/hr per sq ft of hearth area is 8200 divided by the hearth area raised to the 0.435 power. If the loading rate is taken as 2 lb dry solids per hour per sq ft of hearth area and the production rate is 2000 lb/mg of dry solids, the heat loss (Btu/lb DVS) can be estimated as 1160 divided by the design capacity (mgd) raised to the 0.435 power. Thus, for a 10 mgd plant, the radiation and convection loss will be about 426 Btu/lb DVS. The minor losses from the incinerator are, therefore, about 900 Btu/lb DVS. Heat available for combustion products (H_a) can be estimated as 10,000 Btu/lb DVS minus 900 Btu/lb DVS minus the 6054 Btu/lb DVS needed to evaporate the water content or 3046 Btu/lb DVS. Equating equation (14) to 3046 Btu/lb DVS yields a value of 31.5% for E_x, indicating that some auxiliary fuel is required to hold the flue gas temperature at 800°F.

The higher heat value for fuel oil is about 19,000 Btu/lb or 140,000 Btu/gal. A fraction of this heat, however, is lost in the combustion products of the fuel oil. The heat lost per pound of fuel oil burned with no excess air is approximately ($700 + 4.14T_s$) Btu/lb fuel oil. If the amount of fuel oil used is expressed as gallons of fuel oil per ton of DVS, (R_f) the heat contributed by the fuel oil per lb DVS can be calculated as follows:

$$\text{Btu/lb DVS} = R_f(67.42 - 0.0152\, T_s) \tag{15}$$

Thus, since the heat deficit needed to hold the value of E_x at 0.5 with a flue gas temperature of 800°F was 277 Btu/lb DVS, it can be seen that the value for R_f is about 5 gal. of fuel oil per ton of DVS.

In general, when H_a and T_s are known, the value for E_x can be calculated as follows:

$$E_x = (H_a - 535 - 2.55T_s)/(2.09T_s - 177) \tag{16}$$

If the computed value for E_x is less than the recommended minimum of 0.5, E_x is set at 0.5 and the fuel requirement can be calculated as follows:

$$R_f = (3.6T_s + 446.5 - H_a)/(67.42 - 0.0152T_s) \tag{17}$$

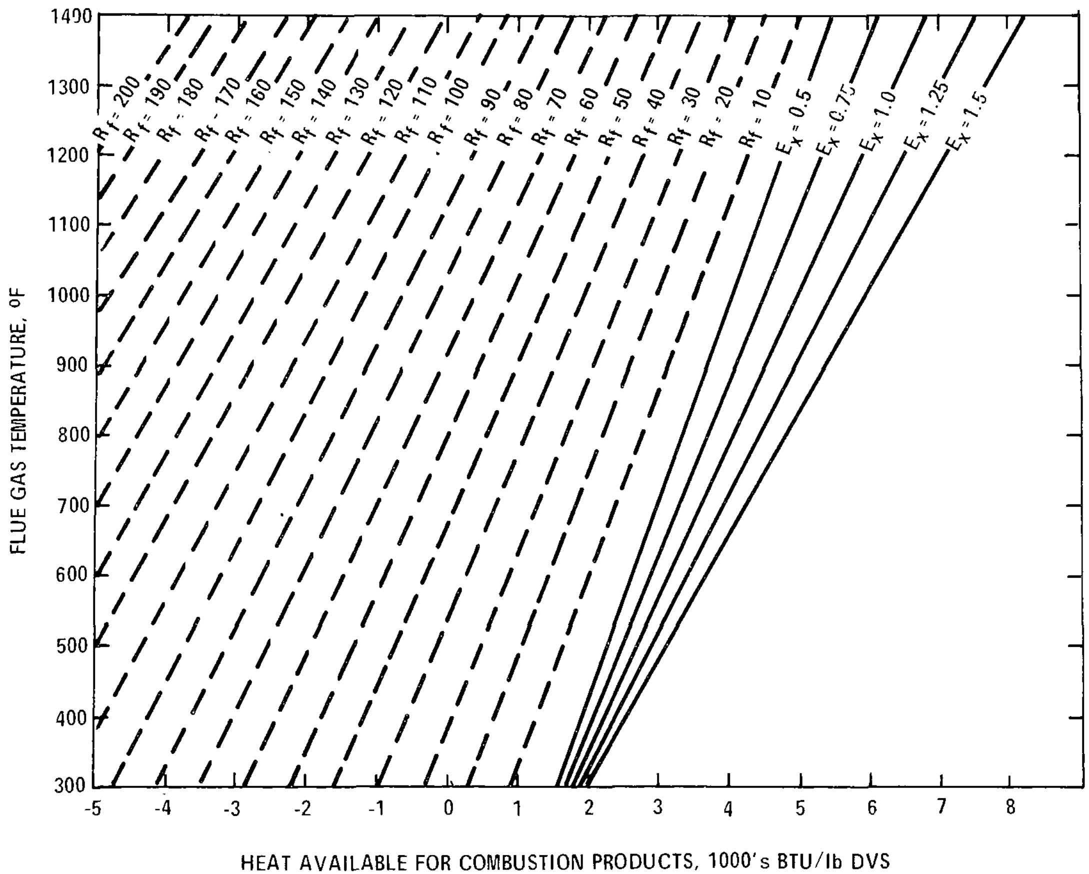

Figure 5. Auxiliary fuel (R_f = gal fuel oil/ton DVS) shown by dashed lines and excess air ratio (E_x = air supplied for combustion/stoichiometric amount) shown by solid lines for holding incinerator flue gas temperature at any set point as functions of heat available for combustion products.

These relationships are shown in Figure 5 as functions of H_a for T_s for easy reference. To find the conditions for which the combustion process will be self sustaining, R_f can be set equal to zero in equation (17). For example, the flue gas temperature achievable with no auxiliary fuel is expressed as follows:

$$T_s = (H_a - 446.5)/3.6 \tag{18}$$

It is also of interest to find the sludge moisture content which can be tolerated for self-sustaining combustion at any flue gas temperature. The pounds of water per pound of DVS (W_s) below which the process will require no fuel can be calculated when the net heat content of the DVS is 9100 Btu/lb DVS as follows:

$$W_s = (9100 - 446.5 - 3.6T_s)/(1008.5 + 0.505T_s) \tag{19}$$

Thus, it can be seen that the value for W_s is 4.09 at 800°F, 3.34 at 1000°F, 2.69 at 1200°F and 2.11 at 1400°F. If the sludge is 70% volatile, these values will correlate to dry solids concentrations of 25.9%, 30.0%, 34.7% and 40.4% at 800, 1000, 1200, and 1400°F, respectively. Thus, it can be seen that the flue gas temperature achievable with no auxiliary fuel is very dependent on the water content of the sludge.

When an afterburner is provided to raise the flue gas set point temperature (T_s) to a higher temperature (T_i), usually 1400°F, to prevent the escape of odors, the total amount of fuel used is calculated as follows where the value of E_x is found from equation (17), and H_a is evaluated at the higher temperature (T_i).

$$R_f = (535 - 177E_x + (2.55 + 2.09E_x)T_i - H_a)/(67.42 - 0.0152T_i) \tag{20}$$

Fuel requirements for thermal cycling can also be computed with reasonable accuracy using the methods given in ref. (22). However, the number and size of the incinerators and the duty cycles must be known. An example worked out in ref. (23) showed that a 10 mgd secondary plant with anaerobic digestion can incinerate 9845 lb dry solids per day using two 510 sq ft hearth area incinerators which use 1475 Btu/lb DVS for thermal cycling.

Total fuel consumption in 8 separate plants for 16 operating periods is reported in ref. (22). The heat content of the dry volatile solids ranged from 9500-14,000 Btu/lb DVS, and the operating flue gas temperature ranged from 685-1360°F. Percent solids in the sludge ranged from 13.5% to 48%, and the volatile fraction ranged from 0.43 to 0.65. Total auxiliary fuel used averaged 3382 Btu/lb DVS and ranged from zero to 6178 Btu/lb DVS. The fuel consumption reported is in reasonably good agreement with the relationships presented here, but unknowns such as fuel used for thermal cycling and approximate values for some of the variables make accurate comparison impossible.

In order to assign a median value to fuel consumption for incineration, assume that the DVS have a heat value of 10,000 Btu/lb, the miscellaneous losses are 900 Btu/lb DVS, the solids content of the sludge is 25% of which 50% are volatile. The 50% value is more characteristic of anaerobically digested sludge. If the flue gas operating temperature is 800°F, the value for H_a will be 625 Btu/lb DVS and the fuel consumption will be 2698 Btu/lb DVS or 49 gal. of fuel oil per ton of DVS. The 1475 Btu/lb DVS fuel requirement for thermal cycling is characteristic of a 10 mgd plant which is near the lower limit of plants practicing incineration. Thus, 750 Btu/lb DVS might be a more appropriate estimate for thermal cycling. Adding this to the operating fuel requirement gives a total of 3448 Btu/lb DVS which is close to the average of 16 examples given in ref. (22) of 3382 Btu/lb DVS. If an activated sludge plant produces 2000 lb/mg of dry solids which are 70% volatile and anaerobically digests all sludge with a reduction of 50% in the volatile solids, the amount of volatile solids to be incinerated will be 700 lb/mg. The estimated fuel usage will, therefore, be 3448 x 700 or 2.41 million Btu/mg. If the electrical power equivalent is taken as 10,500 Btu/kwh, the energy consumption for incineration can be estimated as 230 kwh/mg.

Trucking of Sludge To Land Disposal:

Trucking of dewatered sludge to a land disposal site will generally require less energy than incineration. For example, if sludge is dewatered to a density of 55 lb/cu ft or 0.743 tons/cu yd and hauled in a 10 cu yd dump truck with an average gasoline mileage of 4.5 miles/gallon gasoline, usage can be expressed as 0.06 gal/ton-mile, based on the one-way distance. Furthermore, if the energy content of gasoline is taken as 140,000 Btu/gal and the electrical energy equivalent of heat energy as 10,500 Btu/kwh, the energy cost of sludge hauling can be expressed as 0.8 kwh/ton-mile. If the one-way hauling distance is 20 miles, and the activated sludge plant produces 2000 lb/mg of undigested sludge or 1300 lb/mg of digested sludge, the energy cost for hauling dewatered sludge will be 20 x 0.8 or 16 kwh/mg without digestion or 10.4 kwh/mg with digestion.

Trucking of liquid sludge to land disposal can use as much or more energy than incineration of dewatered sludge, depending on the solids content of the sludge and the distance hauled. Energy used for liquid sludge trucking is directly proportional to the distance hauled and inversely proportional to the solids content of the sludge. For example, if 4% solids content sludge is hauled in a 2500 gallon tank truck having an average gasoline mileage of 4.5 miles/gallon, the energy consumed can be expressed as 1.07 gallons of gasoline per ton per mile of one-way distance hauled. Again assuming the energy content of gasoline as 140,000 Btu/gal and the equivalent of one kwh as 10,500 Btu, the energy used for hauling 4% liquid sludge is 14 kwh/ton-mile. Thus, if an activated sludge plant produces 1300 lb/mg of digested liquid sludge and the sludge is hauled 20 miles one-way to land disposal, the energy used is 14 x 20 x 1300/2000 = 182 kwh/mg. Since the energy cost for hauling is inversely proportional to the solids content, it can be seen that if the sludge hauled had been 3.2% solids, the energy used would have been equivalent to the value estimated for incineration of 230 kwh/mg.

SECTION 7

POTENTIAL FOR ENERGY RECOVERY

In activated sludge plants, sludge production is about 2000 lb of dry solids per million gallon treated. Since this sludge is usually 65-80% volatile, the organic dry solids represent a resource of heat energy which can be recovered to produce mechanical or electrical energy at the plant site. Raw wastewater has a suspended solids concentration of about 225 mg/l, and about 60% of the suspended solids can be removed in the primary settler. Production of primary sludge will, therefore, be 1125 lb/mg and if the sludge is 60% volatile, production of volatile solids will be about 675 lb/mg. Volatile solids production in the activated sludge process is about 0.64 lb/lb BOD removed at an SRT of 3-5 days. Thus, volatile sludge production in the activated sludge process is about 750 lb VSS/mg or 933 lb/mg of dry solids. Total sludge production in the activated sludge plant is about 2060 lb/mg of suspended solids or 1425 lb/mg of volatile solids.

The most commonly used process for recovering energy from the organic component of the sludge is anaerobic digestion of the sludge to produce digester gas. Reduction of volatile solids during digestion is in the range of 50-60% with about 15 scf of digester gas produced per lb of volatile solids destroyed. Thus, production of digester gas will be about 10,700 scf/mg when the more conservative estimate of 50% reduction is used. The higher heat value for digester gas is about 600 Btu/scf. When the gas is used as fuel for internal combustion (IC) engines, the energy conversion rate is in the range of 7000-8500 Btu/hp-hr. If an average conversion rate of 8000 Btu per hp-hr is used, the energy recovered will be about 800 hp-hr/mg or 33 hp per mgd of activated sludge plant capacity. If the mechanical energy is used to generate electrical energy using an electric generator with 96% efficiency, the electrical energy production will be about 573 kwh/mg. This represents 50-70% of the total plant electrical requirements, depending on plant size. Waste heat rejected by the diesel IC engines can be recovered from the engine jacket water to heat the digesters. Roughly 25% of the heat in the digester gas supplied to the IC engines can be recovered from the jacket water. The heat recovered from the jacket water will be about 1.6 million Btu/mg which is near the center of the estimated heat requirement of 2.3-1.4 million Btu/mg. Thus, some auxiliary fuel may be needed for heating the anaerobic digesters.

Another energy recovery scheme which has been proposed (24-25) for large plants where ultimate disposal of the sludge is a difficult problem is the concept of incinerating all of the sludge and recovering heat from the incinerator flue gases by means of waste heat boilers often called economizers. This scheme can also be applied to multiple hearth furnaces used for lime recalcination or activated carbon regeneration. Although suppliers of waste heat boilers feel that the exit gas temperature can be as low as 300-400^oF before corrosion becomes limiting, a more conservative design value which might be more appropriate for wastewater treatment plant installations in 500^oF.

The total or gross amount of heat recovered in the waste heat boiler equals the difference in enthalpy of the flue gases across the boiler. The net amount of heat recovered from the dry volatile sludge solids alone can be found by subtracting the sum of the miscellaneous losses and the enthalpy of the gas stream at the boiler exit temperature (T_o) from the hhv of the DVS. Therefore, if the hhv of the DVS and the miscellaneous losses are fixed, at say 9100 Btu/lb DVS, the net amount of heat recovered is a function of T_o and E_x. Both T_o and E_x should be minimized to maximize the net heat recovered. E_x is minimized when the set point temperature (T_s) is as great as allowed by the incinerator materials. A value of 1100^oF will be used here as the highest practicable value. Where control of odors is important, or where air pollution control standards demand it, an afterburner may be required to raise the flue gas temperature from 1100^oF at the incinerator exit to 1400^oF at the entrance of the waste heat boiler. The value for E_x, however, will be determined by T_s, as shown by equation (16).

Flue gases are composed of superheated steam resulting from the water content of the sludge and the products of combustion for the DVS and the auxiliary fuel, if any is used. From equation (13) it can be seen that the heat recovered from the water content of the sludge will be $0.505(T_i - T_o)W_s$, where T_i is the temperature at the inlet of the waste heat boiler and T_o is the temperature at the exit.

Heat recovered in the waste heat boiler from the volatile solids combustion products per lb DVS is $(2.55 + 2.09E_x)(T_i - T_o)$, as shown by equation (14). The fraction of excess air (E_x) is computed from equation (16) using a value of 1100^oF for T_s. E_x must be set equal to 0.5 if the computed value is less than 0.5.

The amount of heat recovered from the auxiliary fuel products of combustion is $0.0152(T_i - T_o)\ R_f$, where R_{fo}(gal. fuel oil/ton DVS) is the amount of fuel required to hold T_i at 1100^oF when no afterburner is required or at 1400^oF when an afterburner is used. The amount of auxiliary fuel (R_f) is computed from equation (20) by evaluating H_a at the temperature T_i.

The total amount of heat recovered in the waste heat boiler is the sum of the three components quantified above and can be expressed as follows:

$$\text{Btu/lb DVS} = (0.505W_s + 2.55 + 2.09\ E_x + 0.0152\ R_f)(T_i - T_o) \qquad (21)$$

The net heat recovered from the volatile sludge solids alone can be found by subtracting the miscellaneous losses (900 Btu/lb DVS), the enthalpy of the water content of the sludge given by equation (13) by substituting T_o for T_s, and the enthalpy of the products of combustion of the DVS given by equation (14) with T_o substituted for T_s from the hhv of the DVS (10,000 Btu/lb DVS). The value used for E_x in equation (14) is computed from equation (16) except where the computed value for E_x is less than 0.5, in which case, a value of 0.5 is used for E_x. Thus, it can be seen that the net heat recovered is a function of only T_o, T_s, and the water content of the sludge. The computed value for net heat recovered from the DVS is shown in Figure 6 by the solid lines, assuming a value of 1100°F for T_s, 900 Btu per lb DVS for miscellaneous losses, and a hhv of 10,000 Btu/lb DVS for the DVS. It can be seen from Figure 6 that the net heat recovered from the DVS is zero when F_s is 23.5% with a boiler exit temperature of 500°F and when F_s is about 21% with a T_o value of 350°F.

The total amount of heat recovered from the DVS and the auxiliary fuel is shown in Figure 6 by the dashed lines. Fuel needed to hold the set point temperature at 1100°F is zero when F_s has a value above about 32.2%. The vertical distance between the 1100-500°F line and 1400-500°F line is the heat recovered from the auxiliary fuel used in the afterburner.

Computed values for percent excess air and auxiliary fuel used in making estimates of the amount of heat recovered are shown in Figure 7. For a set point temperature of 1100°F, the combustion process is self-sustaining when F_s is above 32.2%. Thus, E_x is greater than 0.5 and auxiliary fuel without the afterburner is zero when F_s is greater than 32.2%. Auxiliary fuel used in the afterburner is the difference between the two dashed lines.

Mechanical energy for direct driving of pumps and blowers can be produced at the plant by allowing steam from the waste heat boiler to expand through a steam turbine. Maximum energy available from each pound of steam can be found from steam tables by assuming that the steam expands isentropically from the inlet conditions to the pressure provided in the condenser. Theoretical efficiency is usually expressed as pounds of steam used per kwh produced defined as the isentropic enthalpy drop divided by 3413 Btu/kwh. Theoretical steam rates for typical inlet conditions are shown in Table 8.

The amount of heat used to produce the steam is the enthalpy at the turbine inlet minus the enthalpy of condenser water returned to the waste heat boiler. Therefore, if the turbine is supplied with 600 psig steam at 750°F and the turbine is equipped with a condenser operating at 2" Hg, the heat added to the steam is 1379 Btu/lb steam at the inlet minus 70 Btu/lb steam in the condenser water or 1309 Btu/lb steam used in the turbine. Multiplying this value by the steam rate of 7.08 lb/kwh gives the amount of heat used to generate one kwh: 9268 Btu/kwh. Thus, the theoretical thermal efficiency is 3413/9268 or 36.8%.

To account for turbine inefficiency a factor must be applied to the theoretical steam rate. In general, turbines with lower speeds (rpm) and greater horsepower are more efficient. Turbines with horsepower ratings in the 5000-15,000 hp range and speeds in the 7500-10,000 rpm range have a quoted efficiency of about 76%. Therefore, the steam rate will be 7.08/0.76 or 9.32 instead of the theoretical value of 7.08. Industrial

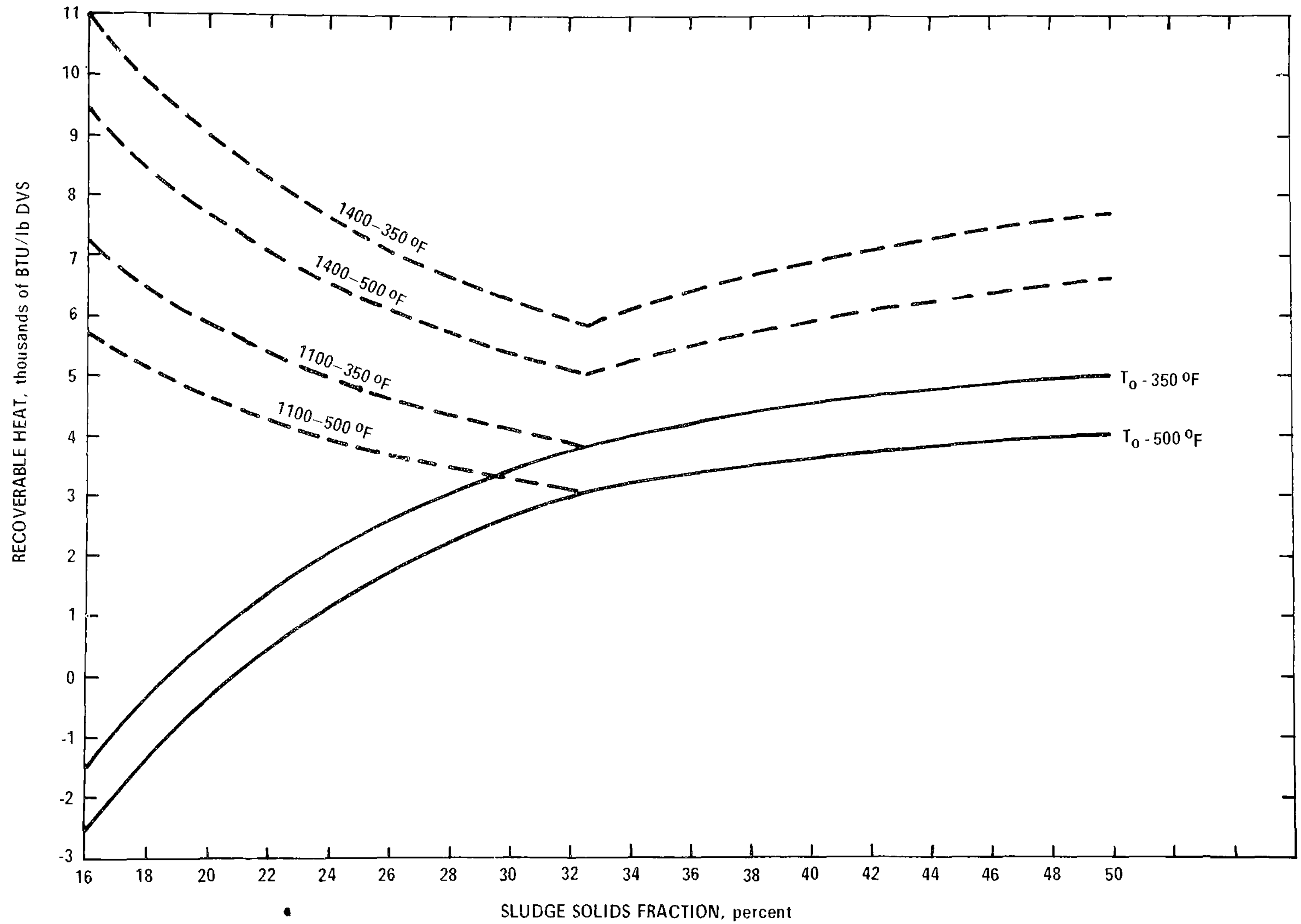

Figure 6. Amount of heat (BTU/lb.DVS) recoverable in the waste heat boiler. Solid lines show heat recoverable from the DVS alone. Dashed lines show total recoverable heat from both DVS and auxiliary fuel. Flue gas set point temperature is 1100°F. Afterburner used to raise flue gas temperature to 1400°F. Boiler exit temperatures are 500° F and 350° F.

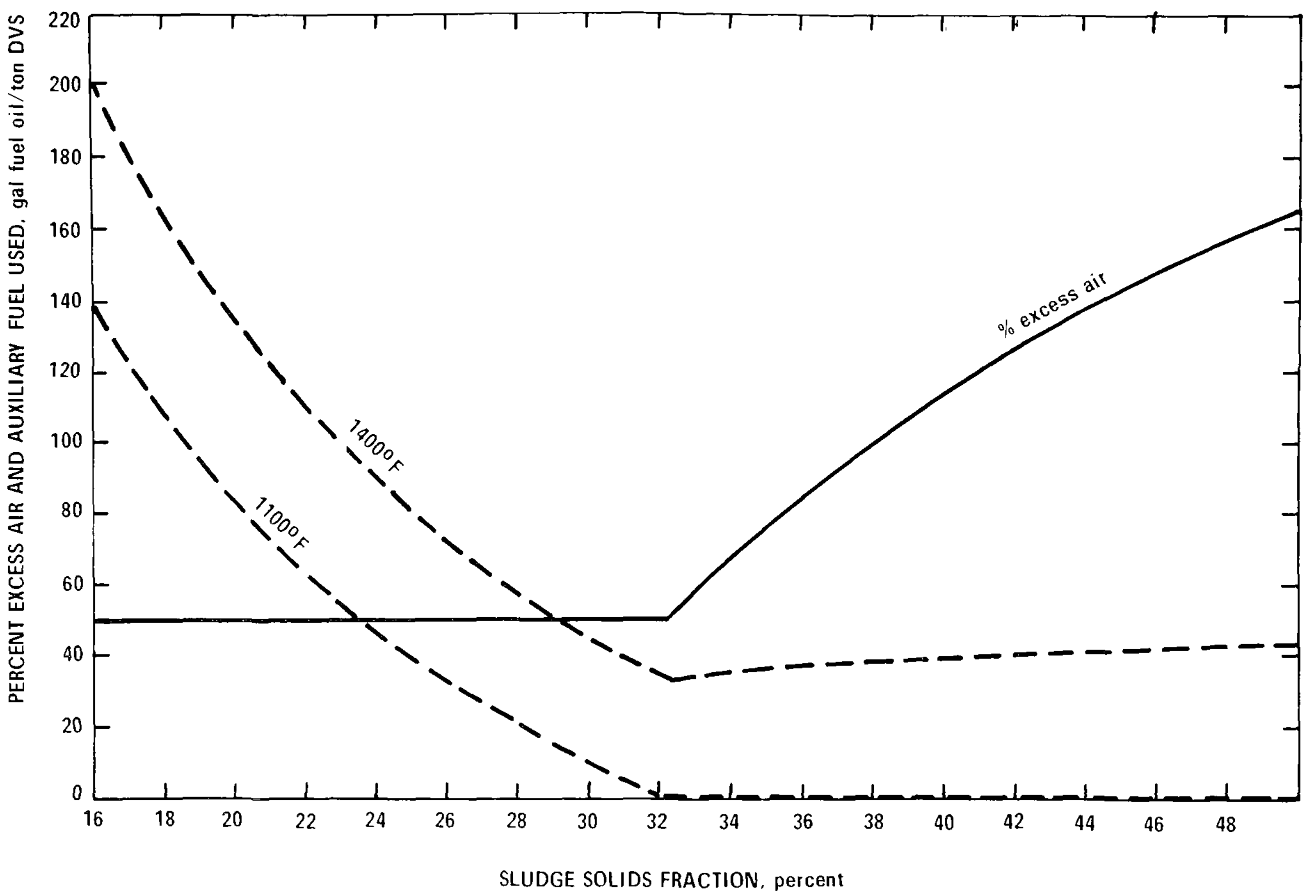

Figure 7. Excess air ratio shown by solid line to hold incinerator flue gas temperature at 1100° F. Auxiliary fuel required is shown by dashed lines for combustion of DVS at 1100° F and for raising the gas temperature to 1400° F with an afterburner.

TABLE 8. THEORETICAL STEAM RATES (lbs/kwh)

	250 PSIG 550°F	400 PSIG 750°F	600 PSIG 750°F	600 PSIG 850°F	900 PSIG 900°F	1500 PSIG 900°F	2000 PSIG 950°F
2" HGA	8.78	7.36	7.08	6.66	6.26	6.08	5.84
4" HGA	9.67	7.98	7.64	7.17	6.69	6.48	6.20
0 PSIG	14.57	11.19	10.40	9.64	8.74	8.26	7.78
50 PSIG	26.75	17.56	15.36	13.98	12.06	10.94	10.07
100 PSIG	42.40	23.86	19.43	17.64	14.50	12.75	11.55
200 PSIG	-	43.51	29.00	26.33	19.45	15.84	13.96
300 PSIG	-	-	43.72	39.70	25.37	18.94	16.19
400 PSIG	-	-	-	-	33.22	22.32	18.49
600 PSIG	-	-	-	-	63.40	30.75	23.63

synchronous electric generators in the range of 3000-5000 kwh have efficiencies between 95-97%, depending on the percent load. Therefore, the steam rate used to predict electrical power generation will be 9.32/0.96 or 9.7 lb/kwh. With this steam rate the thermal efficiency of the turbine and generator combined will be 3413/(9.7 x 1309) or 26.9%. The heat used to produce one kwh of electrical energy can be estimated as 9.7 lb steam/kwh times 1309 Btu/lb steam or 12,697 Btu/kwh. If the heat recovery rate in the waste heat boiler (Btu/lb DVS) is divided by the heat used to produce electrical energy (Btu/kwh), an overall conversion rate of kwh/lb DVS can be found. For example, if the sludge incinerated is 40% solids, 70% volatile, and the waste heat boiler operates over the 1400-350^{o}F range, the total amount of heat recovered will be about 6900 Btu/lb DVS, and this value divided by 12,697 Btu/kwh gives 0.5434 kwh/lb DVS. Heat recovered from the DVS alone is 4550 Btu/lb DVS which corresponds to a conversion rate of 0.358 kwh/lb DVS.

Since activated sludge plants produce about 1400 lb/mg of DVS, these values are equivalent to 761 kwh/mg and 501 kwh/mg for total recoverable electrical energy and net recoverable energy from the DVS alone. These values can be compared to the 573 kwh/mg found earlier for anaerobically digesting the sludge and using the digester gas as fuel for IC engines. This procedure can be used for finding gross and net recoverable electrical energy for any of the heat recovery estimates shown in Figure 6.

This analysis shows that energy recovery using a waste heat boiler to salvage heat from incinerator flue gases is competitive with anaerobic digestion only under the most favorable conditions. For example, heat losses from the waste heat boiler, which might be as much as 10%, have been neglected and the turbine efficiency used corresponds to turbines used only in very large plants. Where sludge with 40% dry solids is incinerated, and the flue gas temperature is raised to 1400^{o}F using auxiliary fuel, power production (assuming a 10% heat loss in the boiler) will be about 38 hp/mgd. Thus, a 5000 hp turbine would be installed in a plant treating about 130 mgd of wastewater with the activated sludge process. The analysis has also shown that the moisture content of the incinerated sludge is a critical parameter if maximum power recovery is the goal.

The principal advantage of the incineration with heat recovery scheme is that it minimizes the mass of residual for ultimate disposal. Another advantage is that low pressure steam can be tapped off the turbine for building heat or for dewatering liquid sludge. Also, when air pollution standards demand that the flue gas temperature be raised to 1400^{o}F with auxiliary fuel, a part of the heat supplied by the fuel can be recovered in the waste heat boiler.

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-78-149		

4. TITLE AND SUBTITLE	5. REPORT DATE
TOTAL ENERGY CONSUMPTION FOR MUNICIPAL WASTEWATER TREATMENT	August 1978 (Issuing Date)
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Robert Smith	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Municipal Environmental Research Laboratory--Cin, OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	1BC611
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Same as above	Inhouse (Jan-Dec 1977)
	14. SPONSORING AGENCY CODE
	EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Robert Smith 513/684-7624

16. ABSTRACT

Quantities of all forms of energy consumed for collection and treatment of municipal wastewater are estimated. Heat energy is equated to electrical energy by a conversion factor of 10,500 Btu/kwh. Total energy consumption, expressed as kwh/mg of wastewater treated, ranges from 2300-3700 kwh/mg. Energy used for construction of the treatment plant and the sewerage system represents 35-55% of the total energy consumed. The remainder used for plant operation is predominately (65-75%) electrical energy. The use of high efficiency aeration devices combined with good maintenance practices appears to offer the best opportunity for conservation of energy within the plant. Recovery of energy from the sludge produced at the plant can be accomplished by anaerobically digesting the sludge and using the digester gas as fuel for internal combustion engines. In large plants, when the sludge is sufficiently dewatered, it is also possible to recover energy by incinerating the dewatered sludge with production of steam in a waste heat boiler. The steam can then be used within the plant or expanded through a steam turbine to produce mechanical or electrical energy.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Sewage Treatment *Sewage Treatment--Water Treatment Sewers *Electric Power Demand	Wastewater Treatment Processes Sewage Treatment Plants Energy Consumption Energy Recovery	13B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to public	Unclassified	51
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE. 1978— 757-140/1426