J. ENVIRONMENTAL SYSTEMS, Vol. 6(3), 1976-77

ENERGY BALANCE FOR ANAEROBIC DIGESTION

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ABSTRACT

A model is developed which describes the energy balance of an anaerobic digestion system for energy recovery from organic wastes. The model is used to evaluate the energy efficiency of the process which consists of pre-treatment including primary shredding, magnetic separation, trommel screening, secondary shredding and air classification of the organic fraction; anaerobic digestion yielding methane fuel gas; gas scrubbing for removal of carbon dioxide and hydrogen sulfide; and dewatering of the waste solids. The results indicate that energy efficiencies for the entire process, excluding transportation of input and output materials, of 48 to 65 per cent are possible; and, 20 to 30 per cent are achievable with present technology. The system is relatively insensitive to front-end and back-end power requirements and to the energy needed for digester operation and maintenance. The most significant factor influencing energy conversion efficiency is the rate and degree of completion of the digestion process.

Introduction

Anaerobic digestion of sewage is employed at most municipal waste-water treatment plants in the United States for the stabilization of sludge so that ultimate disposal is less costly and more sanitary. The production of methane is recognized as a beneficial side effect, but maximization of methane production has not been a primary design and operation objective. However, the great demand for clean-burning natural gas had prompted interest in its

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doi: 10.2190/4HJV-0BNX-Y6RQ-LJ4R
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supply from renewable resources such as solid wastes. Anaerobic digestion is a potential method for converting waste materials to fuel gas. The purpose of this paper is to describe a model of the energy efficiency of the process and to discuss the consequences suggested by the model.

WASTE GENERATION

The sources of organic wastes suitable for use as digester feed materials include sewage, municipal solid waste and agricultural wastes. Anderson has estimated that the 1971 generation of sewage sludge was 11 million metric tons dry weight [1]. A U.S. Environmental Protection Agency (EPA) estimate of total sewage solids for 1973 was 17.2-19 million dry tons, of which approximately 70 per cent, i.e., 12.7 million metric tons, was volatile solids (VS) susceptible to anaerobic digestion [2]. The heat of combustion of sewage solids is 4400 cal/g VS and therefore the potential energy content of sewage wastes is 56.5×10^{15} cal/yr. An even greater amount of organic solid wastes is available from municipal refuse. The most recent EPA estimate is that 66 million dry tons of organic matter are generated each year and that the net energy content of this refuse is approximately 300×10^{15} cal. Agriculture is a significant source of organic wastes. It is estimated that organic wastes amount to 309 million tons from crops and 196 million tons from animals [2]. The potential recovery of all of these quantities is doubtful and only wastes from large feedlots are presently considered a feasible source of organic material.

Waste generation is increasing at a faster rate than population, and total annual wastes are expected to grow by 3-4 per cent per year for the foreseeable future [3]. The quantity of energy available from these sources in the year 2000 would be 2.6 times the amount available today. In this context, wastes may be viewed as a limited but infinitely renewable resource. Various estimates of the total amount of methane gas producible through anaerobic digestion range from 5 to 25 per cent of the present national natural gas consumption.

POTENTIAL FOR ANAEROBIC DIGESTION

It is apparent that new sources of gas supply must be sought. The United States will become increasingly dependent upon gas made available through increased exploration, accelerated leasing of federal lands, production of synthetic gas from coal and oil (SNG), importation of liquefied natural gas (LNG), and development of

Alaskan gas resources. Gas provided by new technologies is expected to cost between $35 and $70 per 1000 cubic meters with imported LNG expected to be even higher, relative to the controlled price of about $18/1000 m^3 for natural gas. The environmental costs of new technologies and costs of dependence upon foreign gas supplies make the new supplies even less attractive.

On the other hand, anaerobic digestion of organic wastes has a positive environmental impact as a solid waste treatment technique. Anaerobic production of biomethane could provide 5-25 per cent of the current level of demand for gas, perhaps more in a few decades, according to the estimates presented in the previous section. For these reasons, this resource has recently gained considerable attention. A realistic assessment of the energy balance of the anaerobic digestion of municipal wastes in conjunction with the development of an energy efficiency model is now presented.

Development of the Model

SUBSTRATE ENERGY

The energy content of digester inputs must be known in order to assess over-all energy efficiency. The variable nature of this material makes exact analysis impossible, but reasonable averages can be developed from available data. The average energy content of municipal refuse has come under recent study, especially with the growing interest in supplementing coal-fired power plants with refuse as fuel. Analysis of household waste samples by Union Electric Company in St. Louis, Missouri, has determined that partial average constituents are: 7-9 per cent metal, 10-12 per cent of glass, and that the remainder has an energy content of approximately 2800 cal/gm [4].

The U.S. Environmental Protection Agency (EPA) analysis of urban solid refuse in 1971 indicated that there was approximately 2500 cal/gm in 112 $\times$ 10^6 metric tons of dry garbage that year [3], and this figure has become the generally accepted value for municipal refuse. Gilbert Associates of Pennsylvania present data in rough agreement with the EPA [5]. Their analysis of typical Northeastern garbage shows an energy content of 2544 cal/gm in 1968, and projects an increase to 2622 cal/gm in 1975, 2672 cal/gm in 1980, and 2800 cal/gm in 1990, due mainly to the increasing proportions of paper and plastics. The most useful estimates thus appear to be 2610 cal/gm for garbage "as received" in the Northeast metropolitan areas, and 4440 cal/gm for the energy in the dry organic portion.

Table 1. Modified Volatile Solids Destruction (Only Non-refractory Materials Considered) [9]. These Entries Represent the Fraction of Volatile Solids Destroyed, Where 75 Per Cent is Assumed To be the Maximum Achievable

	Solids Retention Time (SRT)–Days				
Temperature, °C	*8*	*10*	*15*	*20*	*30*
35	.41	.43	.46	.47	.49
40	.51	.53	.56	.57	.58
45	.45	.46	.49	.51	.52
50	.59	.60	.63	.65	.66
55	.64	.65	.68	.69	.70
60	.69	.71	.73	.74	.75

OPTIMAL DIGESTION CONDITIONS

The choice of operating conditions for the anaerobic digester has multiple effects upon power consumption and methane production. The choices of some base conditions for the model are listed and explicated below. The effect of variations from the base conditions upon the energy balance is explored with a computer model of the various unit processes.

Single phase digestion—Single phase digestion is assumed in the model because not enough is yet known about the operation of two-phase digestion processes. Experimental data indicate that productivity and efficiency improvements may only be marginal [6]. Lawrence and McCarty present data indicating that single phase digestion of sewage sludge is 99 per cent complete at retention times of twenty-five to thirty days at 35°C [7]. In addition, they indicate that with a ten day retention time, waste assimilation is 98 per cent complete at 35°C, and 90 per cent complete at 25°C. There is still some uncertainty about the kinetic constants of garbage digestion, but the rate for the model system would tend to be lower than many reported values because of the mixed and varying nature of the feed material [8]. Kispert and Wise concluded that anaerobic conversion of cellulosic waste to fuel gas proceeds well under thermophilic conditions (55-65°C) and exhibits a maximum productivity at a retention of five days in the laboratory [8].

In the model presented here, digestion for thirty days at 60°C is deemed to be 100 per cent complete. Table 1, representing VS destruction, has been adapted from Pfeffer and Liebman, and is used to characterize digestive efficiency [9]. The degree of destruction is calculated as:

$$1 - \frac{\text{gm VS out/liter}}{\text{gm VS in/liter}} \tag{1}$$

In the model, the VS destruction is determined from the organic input and from the approach to 75 per cent destruction as shown in Table 1.

pH—The pH must be maintained within the tolerance range of the bacteria; generally the optimum is from pH 6.5 to 7.5. The operating point chosen for the model is pH 7. Since acidic products are generated in the digestion process, alkali must be added to neutralize the solution. Lime is usually added to neutralize excess volatile acids.

Mixing—Continuous mixing is an integral part of achieving high-rate digestion. However, there is no known analytical correlation between digestion efficiency and the degree of mixing. A conservative value of 7.7 metric horsepower (HP) per 1000 cubic meters of digester volume is used here [10]. This value exceeds mixing power in common practice because the garbage/sewage mixture is at the relatively thick level of 10 per cent solids in order to minimize digester volume. Mixing may be accomplished by mechanical impellors, gas recirculation devices or external mixing pumps.

Feed composition—The substrate composition determines both the energy input and the quality of convertible material. The assumed average composition for municipal garbage is given in Table 2. As this is believed to be a conservative estimate of the organic portion, variation of the organic content will be carefully investigated with the model, to determine the effect of the projected increase in the paper content of Northeastern municipal refuse. After shredding, air and magnetic separation, and additional shredding, the garbage will be slurried with sewage sludge and water for the purposes of adding nutrients and diluting the digester influent to 10 per cent solids. It is assumed that sewage solids will constitute 10 per cent of the total influent solids, which is slightly higher than the average proportionate generation of sludge and garbage, but is a reasonable figure for new plants in large cities.

Temperature—The operating temperature, along with influent temperature, strongly determines the total energy input. Energy

Table 2. Average Composition of Municipal Refuse Assumed in Digester System Model Base Conditions [8]

Organic portion:		50%
Paper	35	
Yard Waste	7	
Food Waste	6	
Rags, Wood	2	
Inorganic portion:		50%
Plastic	3	
Glass	9	
Metal	8	
Ash	5	
Moisture	25	
Total		100%

must be expended in raising the temperature of the influent to the operating point, and more must be added to compensate for environmental losses. The base temperature for the anaerobic digestion model is 35°C, since most operating experience has been obtained in the mesophilic range. However, the effect of variations throughout the mesophilic (30-45°C) and thermophilic (50-60°C) ranges is examined with the model.

Detention time—Detention time regulates the ultimate health of the bacterial population by allowing sufficient time for reproduction and strongly determines the amount of material converted into gas. The works of Lawrence and McCarty [7] and Pfeffer and Liebman [9] are used to relate waste assimilation efficiency, detention time and temperature. For a design criterion McCarty suggests that the solids retention time (SRT) be 2.5 times the bacterial replacement growth minimum [11]. The reproduction rate is four days for the appropriate bacteria at 35°C, so that the design SRT should be ten days. Digestion at longer SRT is more reliable but not much more efficient. A reasonable range of SRT for investigation is eight to thirty days, encompassing the lower limits and modern practice. The feed concentration and detention time fix the loading rate, so this latter variable will not be investigated independently.

SYSTEM ENERGY REQUIREMENTS

The production of methane and consumption of power are highly dependent upon the whole set of variables listed above. The relation between power consumption and the major variables is now developed and then explored with an interactive computer program.

Pretreatment of the garbage stream—A plant sized for processing 1000 metric tons of garbage per day is chosen for modeling purposes. The front-end processing consists of primary shredding, magnetic separation, trommel screening, secondary shredding, air classification, and mixing with sewage sludge and water. Operating characteristics for this process scheme are listed in Table 3. After pretreatment, 740 tons remain in the garbage stream, which is 60 per cent organic, 34 per cent water and the remainder undigestible solids. An additional fifty tons of sewage solids (75 per cent volatile matter) is mixed with the waste stream, and sufficient water is added to make up a 10 per cent solids digester influent stream. It is assumed that 75 per cent of the organic material is theoretically digestible, in agreement with Dynatech [8] and Pfeffer and Liebman [9] because of the high paper content, over half of which is very digestible Kraft paper.

Digestion requirements—Power consumption during digestion is split into three components: mixing, heating and pumping. Mixing has been assumed to require 7.7 metric HP per 1000 cubic meters of digester. For the 1000 metric ton/day plant, there are seven digesters of 9,865 m^3 volume, each requiring approximately 77 HP for the mixers in continuous operation.

Heating is needed to raise the digester influent to the operating temperature, and to compensate for environmental losses. This energy is dependent upon the ambient temperature, but may be minimized by designing adequate insultation into the digester. Influent temperatures assumed in the model are: 10°C in winter and 22°C in summer for municipal refuse (close to average ambient temperature). The specific heat of the waste is taken as 0.4 cal/gm-°C [8]. Environmental losses are calculated by using the standard heat transfer equation from Eckenfelder [12]. Vapor heat loss can also be taken into account in the model [9].

Pumping power estimates by Dynatech are based on 20 cm diameter pipes with a conservative friction factor of 0.075 (water flow through a rough pipe has a friction factor of 0.0075) [8]. In

Table 3. Operating Characteristics of Frontend Processing Equipment Used in Anaerobic Digestion Model Systems

Equipment	*Efficiency*	*No. of units*	*Size of unit*	*Daily hours of operation*	*Average hourly power consumed (HP) (averaging period = 1 week)*
Primary shredder	7-15 cm output	2	50 ton/hour	15 hr/6 days per week	450 (850 avg. in use)
Magnetic separator	.95 ferrous metal removed .10 non-ferrous metal rem.	2	50 ton/hour	same	16
Trommel screen	.75 glass removed .50 ash removed	2	50 ton/hour	same	8
Secondary shredder	2.5 cm output	2	50 ton/hour	same	250 (460 avg. in use)
Air classifier	.90 organic through-put .70 plastic removed .15 glass removed	2	50 ton/ hour	same	150 (275 avg. in use)

general, pumping power is difficult to estimate without actual plant drawings. However, preliminary calculations show that this input is less than one per cent of the total energy requirements. Pumping requirements are conservatively estimated at 330 HP operating at a 90 per cent load factor.

Back-end requirements—Final processing for disposal calls for dewatering the effluent sludge and purifying the methane. Energy requirements for barging or trucking the sludge cake are not included here. It is possible that profitable uses for the sludge can be found. Use as fertilizer, strip-mine landfill or conversion into mortar board have all been discussed in the literature.

Empirical data are lacking on sludge dewatering by filtration and centrifugation because the characteristics of the effluent are unknown. Pfeffer used an estimate of 1.5 HP/m^2 of filter area [13], while Dynatech developed the figure of 1.8 HP/m^2 from manufacturers' data [8]. Reasonable operating parameters are an average solution filtration rate of 400 l/hr-m^2 (equivalent to 24 kg of solids/hr-m^2) with 75 per cent moisture in the filter cake and a 95 per cent solids capture efficiency. For the modeled plant size, the vacuum filtration power requirement is 125 HP (15 hours/day, 6 days/week), using the Dynatech value.

Gas purification consists of removal of the acidic gases, CO_2 and H_2S, and then drying the methane. The mono-ethanolamine (MEA) gas scrubbing technique is used in the model system. The basic determinant of power consumption is the heat required to strip the absorbent MEA and make it lean again. Five moles of MEA must be circulated for each mole of CO_2 to be removed.

Gas output—Anaerobic digestion of sewage sludge produces gas which is 60-70 per cent methane, 25-35 per cent carbon dioxide, and has traces of other gases. The conversion efficiency of organic matter to methane depends on the bacteria, the feed material and the digester conditions. Griffith reports gas production of 0.56-1.50 m^3/kg of VS destroyed [14]. According to Eckenfelder [11], gas yield at sewage treatment plants averages 1.0-1.12 m^3/kg of VS destroyed.

A chemical balance for the digestion of cellulose yields equimolar quantities of CH_4 and CO_2. However, some of the CO_2 dissolves in the water and is washed out with the liquid effluent. Gas from digestion of garbage has proportionately less methane than that from sewage sludge because of the high cellulose content. A value of 60 per cent methane is here assumed to be produced from

Table 4. Efficiencies at Base Conditions for the Model Anaerobic Digestion System

Temperature, °C	*Solids Retention Time (SRT)–Days*				
	8	*10*	*15*	*20*	*30*
35	.18	.19	.21	.21	.22
40	.23	.24	.25	.26	.26
45	.20	.21	.22	.23	.23
50	.26	.27	.28	.29	.29
55	.28	.29	.30	.31	.31
60	.31	.31	.32	.33	.33

refuse organic solids versus 65 per cent CH_4 from sewage solids. The rate of gas production is 0.368 m^3/kg of VS destroyed. This rate is conservative and so the effect of variation in this parameter is investigated with the computer model.

Results and Discussion

Process efficiency can be measured in a number of ways. The measure used here is the ratio of useful energy output to useful energy input, from the entrance of the waste at the treatment plant to the point where it exits the plant. The waste can be counted as either a "free good" or as a potential source of energy. For the purposes of this paper, both considerations are noted.

The axes of Table 4 above correspond with those of Table 1. Each element represents the per unit energy efficiency at the indicated SRT and temperature, calculated as energy output (purified methane) divided by energy input (heat value of waste and power used in processing, heating, mixing, filtering and purifying the waste). All entries are for summer operation, refuse composition as in Table 2, equipment operation as in Table 3, and 10 per cent addition of sewage solids on a dry basis.

Energy recovery ranges between 18.5 and 33 per cent. It is apparent that energy production is 90-95 per cent complete at ten days retention versus thirty days. At an SRT of ten days, mesophilic digestion at 40° C and thermophilic digestion at 60° C provide the best results, with net energy recovery improved by 30 per cent at the higher digestion temperature. These results indicate that efficiency of volatile solids reduction dominates all other energy

Table 5. Per Unit Energy Input/Per Unit Energy Output for Model Digester at Base Operating Conditions

Temperature, °C	*Solids Retention Time (SRT)–Days* 8	10	15	20	30
35	.11	.10	.10	.09	.09
40	.09	.08	.08	.08	.08
45	.10	.09	.09	.09	.08
50	.07	.07	.07	.07	.07
55	.07	.07	.06	.06	.06
60	.06	.06	.06	.06	.06

factors. This relation is born out for all of the parameter variations reported below.

The experimental results presented by Pfeffer and Liebman were used here, and are critical in the final determination of energy efficiency [9]. It is not clear that thermophilic digestion will be so distinctly advantageous on a commercial scale. However, as mentioned before, it has been found experimentally that thermophilic digestion can cut the minimum SRT in half and maintain high gas productivity [8].

In addition to overall energy efficiency, the usefulness of a particular energy extraction process can be indicated by how many units of energy must be consumed for each unit of useful energy produced. Table 5 shows the ratio of total processing energy (shredding, mixing, heating, pumping, purifying, etc.) to total output (energy value of the methane) as a function of SRT and temperature. It is readily seen that at most 10.7 per cent of the output energy is consumed in the process, while at best only 5.8 per cent is used. Of course, if the methane is used to run the plant itself before contributing to external gas supplies, additional energy conversion efficiencies would have to be taken into account to determine the complete energy balance. The figures in Table 5 reflect only the non-optimized efficiencies. If less pre-processing and heating energy are required or if higher conversion efficiencies prove feasible (variations which are to be explored in the next section), then processing energy amounts to only 1/40 to 1/100 of the useful product energy. These relationships have been explored with the computer programs but are not discussed in more detail here [15].

Table 6. Energy Efficiency With 50 Per Cent Improved PVSD. All Other Digester Operating Parameters Are at Base Conditions

	Solids Retention Time (SRT)–Days				
Temperature, °C	*8*	*10*	*15*	*20*	*30*
40	.33	.34	.36	.37	.37
60	.44	.45	.46	.47	.47

PARAMETRIC STUDY

The purpose of this section is to present the results of an analysis of the sensitivity of energy conversion efficiency to perturbations of the critical systems variables. The results reported here include the effect of the following on process energy efficiency: ambient air temperature; per cent volatile solids destruction; extent of pre-processing; and front-end power consumption.

Temperature—The computer model was run to determine the effect of colder influent temperatures (winter operation). Net efficiency decreased by only 0.2 per cent at mesophilic temperatures and 0.3 per cent at thermophilic temperatures, or, in other words, there was only 1 per cent change between summer and winter input requirements. Greater insulation, use of solar heating, or siting in warm climates will minimize these losses.

VS destruction—The per cent of volatile solids destruction (PVSD) depends upon the composition and digestibility of the feed material. If the material contains more fats and proteins, or if the cellulose is pre-processed for improved digestibility [9], the production of gas improves greatly. A change in PVSD corresponding to a 50 per cent improvement in the second term of Equation 1 was made, and the computer program run with all other parameters at base conditions. As expected, the net efficiency showed a distinct improvement. Energy efficiency for digestion at 40°C and 60°C is shown in Table 6. The final range was from 33-47 per cent energy recovery, or a linear increase in efficiency since no extra processing penalties were assumed. The value of such an increase in gas production is apparent, and all reasonable possibilities for increasing the volatile solids destruction rate should be investigated.

Table 7. Energy Efficiency for Anaerobic Digestion Under Base Operating Conditions With the Exception of 20 Per Cent More Organics in Feed

	Solids Retention Time (SRT)—Days				
Temperature, °C	*8*	*10*	*15*	*20*	*30*
40	.25	.25	.27	.28	.28
60	.33	.34	.35	.35	.35

Substrate quality—The nature and energy content of the refuse input were varied in order to simulate the effect of pre-processing to increase the digestible fraction of the feed. First the organic content was increased from 0.5 to 0.6 and water was reduced from 0.25 to 0.20. This resulted in a change in the energy content from 2500 to 2777 cal/gm. This yielded a 10 per cent increase in energy efficiency corresponding to a 2-3 per cent increase in net energy recovery. The figures are presented in Table 7.

A nearly equal but opposite effect was achieved by decreasing the organic content to 0.4, increasing the water to 0.3, and raising the level of inorganics. Total heat content was 2333 cal/gm. At a ten day SRT, efficiency was 0.21 versus 0.24 at 40°C and base conditions, and 0.27 versus 0.31 at 60°C and base conditions. Energy efficiency fell off faster with decreasing organics than it improved with increasing organics.

Processing power consumption—Finally the effect of front-end power consumption in energy efficiency was tested. Altogether nearly 1769 HP of power may be in simultaneous operation. However, the effect of doubling the demand had only the same magnitude effect as winter versus summer operation—that is only a 0.2-0.3 per cent decrease in net energy recovery, or one per cent greater consumption at mesophilic and thermophilic temperatures. Thus, the energy requirements for front-end separation and materials recovery is not a significant determinant of over-all energy efficiency. However, increasing the organic content has a marked effect as shown by comparing Tables 4 and 7. Therefore, within the constraints of cost, it is beneficial to increase the degree of pre-processing to remove inorganics and thus increase the organic content of the feed material. It should be noted that other studies have indicated that the salvage value of the recovered inorganics may cover the economic cost of front-end pre-processing [16].

Conclusions

The analysis has shown that anaerobic digestion of garbage has great potential for complementing current efforts in the disposal of waste and augmentation of energy supplies. Anaerobic digestion can add incremental amounts to natural gas supplies. Perhaps more importantly, the digestion of garbage helps minimize environmental impacts of solid waste disposal and fosters a resource conservation ethic. Both material and energy resources are recovered through the process while disposal problems are minimized.

With present technology and no process improvements, anaerobic digestion is a satisfactory but not highly efficient waste processing/ energy recovery system. Only 20 to 30 per cent of the theoretical energy available is recovered. Yet, under the combination of the most favorable conditions investigated here, anaerobic digestion could recapture 48 per cent (mesophilic) to 65 per cent (thermophilic) of the energy available. The most favorable conditions are: high organic content in feed, low processing energy requirements, and a 50 per cent increase in volatile solids destruction. These conditions are reasonable for systems maximizing methane production. Also, anaerobic digestion is handily combined with metals and glass recovery systems, making the economics of the separation processes more attractive.

Anaerobic digestion energy efficiency is fairly insensitive to the amount of power used for pre-processing, mixing, heating, pumping, dewatering, and gas purifying. Consequently, a wide variety of design and siting options are feasible for integrating waste disposal and resource recovery systems. Anaerobic digestion has the added advantage of producing a portable and highly valued fuel which is in increasingly short supply.

Process efficiency is, however, very sensitive to the rate and completeness of the digestion process itself. Advances in the understanding of digestion kinetics and in digester control have reduced detention times and increased feasible loading rates in recent years, but there is still room for improvement. Digestion of garbage with a high cellulose and lignin content is more difficult than the conventional digestion of sewage sludge. The reward for improvement of volatile solids destruction is great in terms of both waste reduction and gas production. Serious effort needs to be directed toward improving the rate and degree of anaerobic decomposition.

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