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RESOURCE CONSERVATION AND UTILIZATION IN ANIMAL WASTE MANAGEMENT - VOLUME III

Utilization of Animal Manures as Feedstocks for Energy Production

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16. ABSTRACT

This study critically examined the feasibility of using thermochemical processes such as combustion, pyrolysis, and partial oxidation and anaerobic digestion as methods for utilizing livestock and poultry manures as renewable sources of energy. Technical, economic, and environmental quality aspects were considered.

Results of this study indicate that livestock and poultry manures can, at best, supply only a small fraction of U.S. energy requirements and cannot signficantly reduce the dependence of U.S. agriculture on petroleum fuels. It was found that livestock and poultry manures generally are not suitable for use directly as fuels or feedstocks for pyrolysis and partial oxidation due to high moisture content.

It also was found that the technical feasibility of manurial biogas production has been adequately demonstrated and a rational basis for system design and operation has been established. Although manurial biogas production is technically feasible, economic feasibility was found to be site specific depending on available biogas utilization options. Odor control appears to be the principal environmental quality benefit associated with manurial biogas production. Potential adverse water quality impacts associated with manures may be reduced, but are not eliminated.

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FOREWORD

EPA is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise, and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life. In partial response to these mandates, the Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, is charged with the mission to manage research programs to investigate the nature, transport, fate, and management of pollutants in ground water and to develop and demonstrate technologies for treating wastewaters with soils and other natural systems; for controlling pollution from irrigated crop and animal production agricultural activities; for controlling pollution from petroleum refining and petrochemical industries; and for managing pollution resulting from combinations of industrial/industrial and industrial/municipal wastewaters.

This phase of the project was initiated to critically examine the feasibility of using thermochemical processes such as combustion, pyrolysis, partial oxidation, and anaerobic digestion as methods for utilizing livestock and poultry manures as renewable sources of energy. Results indicate that livestock and poultry manures can only supply a small fraction of U.S. energy requirements. The information presented is useful in determining which systems will be useful in the development of Best Management Practices for animal waste management systems.

Clinton W. Hall

Clinton W. Hall, Director
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Research Laboratory

ABSTRACT

Temporary but serious shortfalls in supplies of natural gas, liquified petroleum gas, gasoline, and distillate fuels have led to the examination of various opportunities for the agricultural sector to become a producer as well as a consumer of energy. This study critically examined the feasibility of using thermochemical processes such as combustion, pyrolysis, and partial oxidation and anaerobic digestion as methods for utilizing livestock and poultry manures as renewable sources of energy. Technical, economic, and environmental quality aspects were considered.

Results of this study indicate that livestock and poultry manures can, at best, supply only a small fraction of U.S. energy requirements and cannot significantly reduce the dependence of U.S. agriculture on petroleum fuels. It was found that livestock and poultry manures generally are not suitable for use directly as fuels or feedstocks for pyrolysis and partial oxidation due to high moisture content.

It also was found that the technical feasibility of manurial biogas production has been adequately demonstrated and a rational basis for system design and operation has been established. Although manurial biogas production is technically feasible, economic feasibility was found to be site specific depending on available biogas utilization options. Odor control appears to be the principal environmental quality benefit associated with manurial biogas production. Potential adverse water quality impacts associated with manures may be reduced, but are not eliminated.

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SECTION 1

INTRODUCTION

During the past decade, the United States has experienced temporary but serious shortfalls in supplies of natural gas, liquified petroleum gas, gasoline, and distillate fuels. Among the many consequences of these events has been an increased awareness of the finite nature of fossil fuel reserves and the need to develop renewable supplies of energy. Another consequence has been a better understanding of the dependence of production agriculture on fossil fuels. The production of agricultural commodities has been estimated to require approximately 2.6% of the energy consumed annually in the U.S. (Economic Research Service, 1974).

These shortfalls and concerns have led to the examination of various opportunities for the agricultural sector to become a producer as well as a consumer of energy. Consideration has been given to the use of a variety of agricultural residues including livestock and poultry manures as fuels and as feedstocks for physical-chemical and biological energy conversion processes such as pyrolysis and anaerobic digestion.

BACKGROUND

The dry matter content of manures excreted by U.S. livestock and poultry exceeds 100 million tonnes per year (Van Dyne and Gilbertson, 1978). Assuming the average heating value of manurial dry matter to be 1.7×10^{10} joules (J)/tonne (Schlesinger et al., 1978), the potential energy value of manures produced in the U.S. is more than 1.7×10^{18} J/yr. This is roughly equal on the basis of energy content to 300 million barrels of crude oil or 16 million therms of natural gas.

Much of the manure produced by U.S. livestock and poultry is not collectible since it is being produced on pasture or range. Van Dyne and Gilbertson estimated that less than one-half of all livestock and poultry manures can be economically recovered for use elsewhere with almost all collectible manures produced in confinement facilities. Table 1 compares estimates of the quantities of manures produced annually by U.S. livestock and poultry and the quantities that are economically recoverable for use elsewhere. It is noteworthy that dairy cattle are the single largest source of collectible animal manures.

TABLE 1. ESTIMATES OF THE QUANTITIES OF MANURE PRODUCED ANNUALLY BY U.S. LIVESTOCK AND POULTRY AND QUANTITIES OF MANURE THAT ARE ECONOMICALLY RECOVERABLE FOR USE (Van Dyne and Gilbertson, 1978).

	Total Production		Economically Recoverable	
	Dry Weight, 10^6 tonnes/yr	% of total	Dry Weight, 10^6 tonnes/yr	% of total
Beef Cattle (range)	47.3	46.7	1.7	4.1
Beef Cattle (feed lots)	9.5	9.3	9.5	22.6
Dairy Cattle	22.9	22.6	18.5	44.0
Swine	12.1	12.0	5.0	12.0
Sheep	3.5	3.4	1.5	3.7
Laying Hens	3.1	3.0	3.0	7.0
Broilers	1.9	1.9	1.9	4.5
Turkeys	1.1	1.1	0.9	2.1
Total	101.3	100.0	42.0	100.0

TABLE 2. ON-FARM ENERGY CONSUMPTION IN U.S. AGRICULTURE (Economic Research Service, 1974).

	10^{17}J/yr	% of Total U.S. Energy Consumption*
Direct inputs		
Crops		
Petroleum	7.91	1.0
Electricity	0.12	0.02
Livestock		
Petroleum	2.64	0.3
Electricity	0.38	0.05
Subtotal	11.05	1.4
Indirect inputs		
Fertilizer	6.20	0.7
Petroleum	2.05	
Feeds & Additives	1.05	
Animal & Marine Oils	0.38	0.5
Farm Machinery	0.33	
Pesticides	0.12	
	21.18	2.6

* 7.91 X 10^{19}J/yr.

Assuming that possibly 50% of the energy content of collectible animal manures is recoverable in a usable form (Huffman, 1978), roughly 4×10^{17} J of energy is potentially available annually from livestock and poultry manures in the U.S. This represents approximately 15% of total (direct and indirect) on-farm energy consumption in the U.S. and exceeds estimated direct energy consumption for livestock production (Table 2).

OBJECTIVES AND SCOPE

Although the use of livestock and poultry manures as feedstocks for energy conversion processes is attractive in principle, the merits of this approach for utilizing animal manures remain debatable. The objectives of this report are, in the context of U.S. agriculture, to:

1. Examine a) thermochemical processes such as combustion, pyrolysis, and partial oxidation, and b) anaerobic digestion as alternatives for utilizing livestock and poultry manures as renewable sources of energy. These alternatives are characterized in terms of the forms of energy, possible by-products, and residuals produced.

2. Assess the economic incentives for the utilization of animal manures as renewable sources of energy based on: a) the monetary value of the fuel or energy produced, b) opportunities for utilization, and c) opportunities for by-product recovery. These incentives are compared to estimates of production costs.

3. Identify possible environmental quality benefits and negative impacts associated with the above energy conversion processes.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Livestock and poultry manures can, at best, supply only a small fraction of U.S. energy requirements but represent a renewable source of energy that should not be overlooked.

2. Energy produced from animal manures cannot significantly reduce the dependence of U.S. agriculture on gasoline and diesel fuel, and other petroleum products.

Thermochemical Processes

1. Livestock and poultry manures generally are not suitable for use directly as fuels or feedstocks for pyrolysis or partial oxidation due to high moisture content. Broiler litter and manures produced in semi-arid and arid climates are exceptions.

2. Of the thermochemical processes considered (combustion, pyrolysis, and partial oxidation) combustion is the most attractive.

Anaerobic Digestion

1. The technical feasibility of manurial biogas production has been adequately demonstrated and a rational basis for system design and operation has been established.

2. Of the available biogas utilization options, on-site generation of electricity appears to be the most practical and generally applicable.

3. The economic attractiveness of producing biogas for on-site generation of electricity depends on several site specific variables including on-site demand for and cost of electricity, the price to be paid for excess electricity, and opportunities for waste heat utilization.

4. Anaerobic digestion does not enhance the value of manures as feedstuffs. Thus, by-product credits based upon the monetary value of anaerobically digested manures as feedstuffs are not justified.

5. Odor control appears to be the principal environmental quality benefit associated with manurial biogas production. Potential adverse water quality impacts associated with manures may be reduced but are not eliminated.

RECOMMENDATIONS

In future research, emphasis should be placed not only on production but also utilization of energy from livestock and poultry manures.

Thermochemical Processes

1. Emphasis in any future research should be placed on the direct use of manures as boiler fuels.

2. In all future investigations, characterization of manures used as feedstocks and detailed energy and material balances should be basic requirements.

3. Possible environmental quality benefits as well as negative impacts also should be components of any future studies of thermochemical conversion of animal manures into usable energy.

Anaerobic Digestion

1. Biogas production costs and the relationships between these costs and system design and operation should be more rigorously examined.

2. The efficiency and cost as related to engine type (spark ignited, diesel, or gas turbine) of using biogas for on-site generation of electricity also should be more rigorously examined.

SECTION 3

THERMOCHEMICAL PROCESSES

The possibility of using thermochemical processes such as combustion, pyrolysis, and partial oxidation to recover usable forms of energy from livestock and poultry manures has been the subject of recurring interest and limited research for more than a decade. This section reviews the characteristics of these processes and compares the forms of energy and residuals produced. It also examines the suitability of livestock and poultry manures as feedstocks for these processes, trade-offs between energy production and plant nutrient losses, and environmental quality implications based upon the limited data available. These topics address what appear to be the more critical questions concerning the use of manures as renewable sources of energy using thermochemical processes.

PROCESSES

Combustion, pyrolysis, and partial oxidation are the principal types of thermochemical energy conversion processes applicable to organic wastes such as animal manures. Although these processes differ substantially in many respects, they have the common characteristic of employing high temperatures to thermally decompose or crack complex organic molecules into simpler constituents. Depending on the process used, either thermal energy or solid, liquid, and gaseous fuels can be produced. Production of chemical process feedstocks such as ammonia synthesis gas also is possible but will not be considered in this report.

Combustion

Combustion is the simplest and most familiar thermochemical energy conversion process. It produces thermal energy as a final product and ash and other products of combustion as residuals. During combustion, complex organic molecules are thermally cracked, ultimately producing elemental carbon, hydrogen, and possibly sulfur, which are then rapidly oxidized producing heat and commonly light. Residuals include: carbon dioxide (CO_2), carbon monoxide (CO) if combustion is not complete, water, oxides of sulfur (SO_x) if sulfur is present, oxides of nitrogen (NO_x), and ash.

Pyrolysis

Pyrolysis which is also known as destructive distillation also employs high temperatures to crack complex organic molecules into simpler constituents. It differs from combustion in that it is a reducing rather than an oxidizing process and is endothermic. However, the products produced which

include solids, liquids, and gases can have value as fuels. Commonly, one or more of these products are burned to provide the required process heat.

The solid component which is commonly referred to as char contains carbon and ash as principal constituents. The heating value of char produced by pyrolysis of manures is variable depending on ash and carbon content. Ash content is directly related to the composition of the manure used as a feedstock while char carbon content is a function of process conditions. Nelson (1973) reported that increasing the temperature for pyrolysis from 538° C to 815° C decreased the carbon content of poultry manure char from 44% to 36%. Reported heating values for chars produced from manures range from 7.0×10^9 J/tonne (White and Taiganidies, 1971) to 1.8×10^{10} J/tonne (Garner et al., 1972). Garner et al., noted that char produced by pyrolysis of beef cattle manure at 400-500° C was difficult to burn.

Liquids produced during pyrolysis are typically a complex mixture of water, alcohols, light oils, and tars. Garner et al., (1972) reported that the chemical complexity of the oils and tars produced during pyrolysis of beef cattle manures was such that stearic acid was the only compound that could be positively identified. Estimated heating values for light oils and tars were 2.3×10^{10} J/tonne and 3.0×10^{10} J/tonne respectively. Benzene and toluene have been reported to be the principal constituents of light oils produced during pyrolysis of municipal and industrial solid wastes (Sanner et al., 1970).

Both combustible and noncombustible gases are produced during pyrolysis. The major constituents of pyrolysis off-gases are hydrogen (H_2), nitrogen (N_2), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), ethylene (C_2H_4), and ethane (C_2H_6). Longer chain hydrocarbons (C_nH_n) also may be present. The energy content of pyrolysis off-gases, which also is called fuel gas, can vary widely but generally does not exceed 12×10^6 J/m^3 of dry gas (Beck 1981). This is much less than other gaseous fuels such as natural gas which has an energy density of 38×10^6 J/m^3.

Product mix, i.e., the relative quantities of solids, liquids, and gases produced during pyrolysis, depends on the characteristics of the material pyrolyzed, the process temperature, and the possible presence of catalysts. Generally, increasing process temperature increases production of gases and reduces the quantities of oils and tars. Heavy oil can be produced as a principal end product, however, by using steam and carbon monoxide as reactants under high temperature and pressure (Appell et. al., 1971). As previously noted, char carbon content and thus heating value also decreases as process temperature increases.

Partial Oxidation

Partial oxidation is a modification of the pyrolysis process in which a portion of the feedstock is burned in the reactor under controlled conditions to energize the pyrolysis reaction. The principal advantage of partial oxidation as compared to conventional pyrolysis is the reduction of heat transfer problems. The products produced during pyrolysis and partial oxidation are similar and are influenced by the same variables.

Process Comparison

Overall thermal efficiency (the percentage of feedstock energy that ultimately can be converted to heat or power) is the most logical basis for comparing combustion, pyrolysis, and partial oxidation as processes for converting livestock and poultry manures into usable forms of energy. Such comparison, however, is not possible except in very general terms, due to the lack of detailed energy balances for these processes from either full or pilot plant scale studies.

Although no supporting data are available, it appears reasonable to assume that the thermal efficiency of using manure as a boiler fuel should be comparable to that for coal, 60 to 70%. Available data for pyrolysis (Table 3) suggest that 76 to 85% of feedstock energy can be recovered as gas, oil, and char. This is without consideration of process energy requirements or thermal inefficiencies associated with utilization of the fuels produced. Thus, it appears reasonable to conclude that the overall thermal efficiencies of pyrolysis and partial oxidation are at best comparable to and probably less than that for combustion.

TABLE 3. ENERGY BALANCES FOR BATCH AND CONTINUOUS RETORT PYROLYSIS OF BEEF CATTLE MANURE.

	Batch Pyrolysis*	Continuous Retort†
Moisture content of manure, %	3.6	2.91
Yields, per dry tonne of manure		
Gas, m^3	410	663
Oil, ℓ	51	215
Water, ℓ	150	478
Char, kg	342	337
Heating Values		
Manure, J/kg	1.65×10^7	1.77×10^7
Gas, J/m^3	1.68×10^7	4.6×10^6
Char, J/kg	1.69×10^7	1.48×10^7
Oil, J/ℓ. ††	2.5×10^7	2.5×10^7
Energy Balance, J/tonne of manurial dry matter		
Input	1.65×10^{10}	1.77×10^{10}
Output		
Gas	6.89×10^9	3.05×10^9
Oil	1.28×10^9	5.38×10^9
Char	5.78×10^9	4.99×10^9
Total	1.40×10^{10}	1.34×10^{10}
Recovery, %	85	76

* Schlesinger et. al., 1972
† Massie and Parker, 1973
†† Estimated by authors

Perhaps the most significant difference between pyrolysis and partial oxidation and combustion is the form of energy produced. Pyrolysis and partial oxidation are fuel producing processes requiring a subsequent utilization step to produce thermal energy. If the gases, oils, and chars produced by pyrolysis or partial oxidation of animal manures are to be used as boiler fuels, there appears to be no advantage to using these processes instead of combustion. Due to the low energy densities of the gases and chars and the chemical complexity of the oils and tars produced by pyrolysis, use of these products as boiler fuels is most probable.

SUITABILITY OF MANURES AS FEEDSTOCKS

The value of any organic material including animal manures as a fuel or a feedstock for thermochemical processes such as pyrolysis or partial oxidation depend on elemental composition and moisture content. As noted by Whetstone et al. (1974), materials with high carbon and hydrogen contents are most desirable with hydrogen being of greater value. Oxygen is detrimental since it reduces heating value. Sulfur and nitrogen can result in emissions of sulfur and nitrogen oxides, which are classified as air pollutants.

As shown in Table 4, beef cattle feedlot manure compares favorably, on the basis of elemental analysis, with other materials that can be used as fuels or feedstocks for thermochemical processes. The values listed for carbon, hydrogen, etc. are for beef cattle manure as it is produced. As manures accumulate in barns, feedlots, and storage facilities, losses of carbon, hydrogen, nitrogen, and possibly sulfur will occur and ash content will increase due to microbial activity and weathering. Thus, the value of manures as sources of energy also will be reduced.

TABLE 4. ELEMENTAL ANALYSES OF POTENTIAL FEEDSTOCKS FOR THERMOCHEMICAL PROCESSES.

Material	Lignite*	Oil Shale*	Subbituminous* coal	Solid Waste*	Beef Cattle†
Source	ND-Beulah Steam	CO-Green River deposit	WY-monarch seam	Average Municipal Refuse	Feedlot Waste
Carbon,%	42.4	23.8 ††	54.6	35.4	42.6
Hydrogen	6.7	2.6	6.4	4.4	5.5
Oxygen	43.3	12.3	33.8	28.2	23.7
Nitrogen	1.7	0.5	1.0	0.4	2.8
Sulfur	0.7	1.0	0.4	0.2	0.5
Ash	6.2	59.8	3.8	31.4§	24.9
Total	101.0	100.0	100.0	100.0	100.0
Moisture, % wb.	34.8	0.2	23.2	20.7	29.1

* Feldmann (1971)
† Herzog et al. (1973)
†† Includes 4.6% carbon as carbonate
§ Includes metals, glass, ceramics

Thermochemical energy conversion processes consist of three basic components: drying, thermal decomposition, and recovery and utilization of the energy produced (Figure 1). The first two components are endothermic and require thermal energy inputs. The magnitude of these energy inputs is an important factor in determining net energy production. Before the necessary temperatures for thermal decomposition can be achieved, removal of moisture is necessary. This makes feedstock moisture content a critical factor.

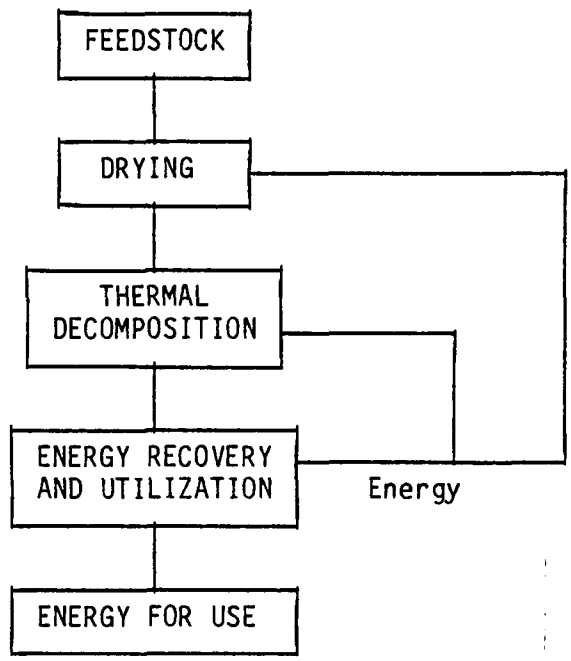

Figure 1. Basic components of thermochemical processes.

The relationship between moisture content, % wet basis (wb.), and the height of water present on a total solids basis is illustrated in Figure 2. Figure 3 shows the relationship between: a) the heat required for evaporation of moisture in the feedstock, and b) the feedstock moisture content, % wb., for an initial feedstock temperature of 20°C. Assuming a gross energy (heat) value for manurial dry matter of 12,755 kJ/kg (Garner et al., 1972) and a thermal efficiency of 65%, feedstock moisture content must be less than 71% wb. for combustion to be theoretically self sustaining. This assumes complete combustion of carbon, hydrogen, and sulfur and does not consider evaporation of reaction water.

As illustrated in Figure 3, feedstock moisture content must be below 60-65% wb for significant net energy production via combustion. For pyrolysis, it has been estimated that an additional 930 kJ/kg of total solids is required (Garner et. al., 1972). This results in an additional reduction of net energy production potential.

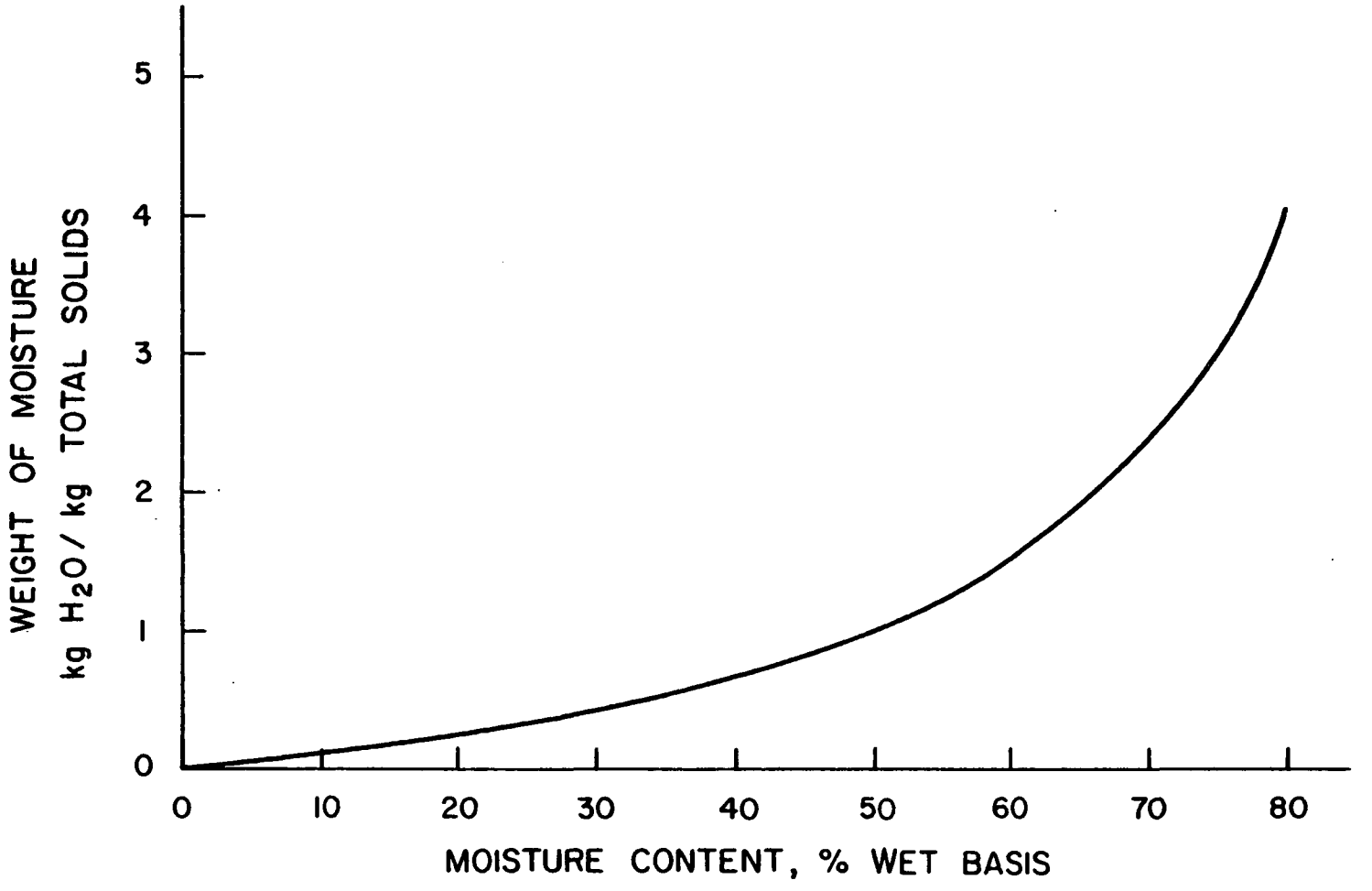

Figure 2. Relationship Between Moisture Content and Weight of Moisture.

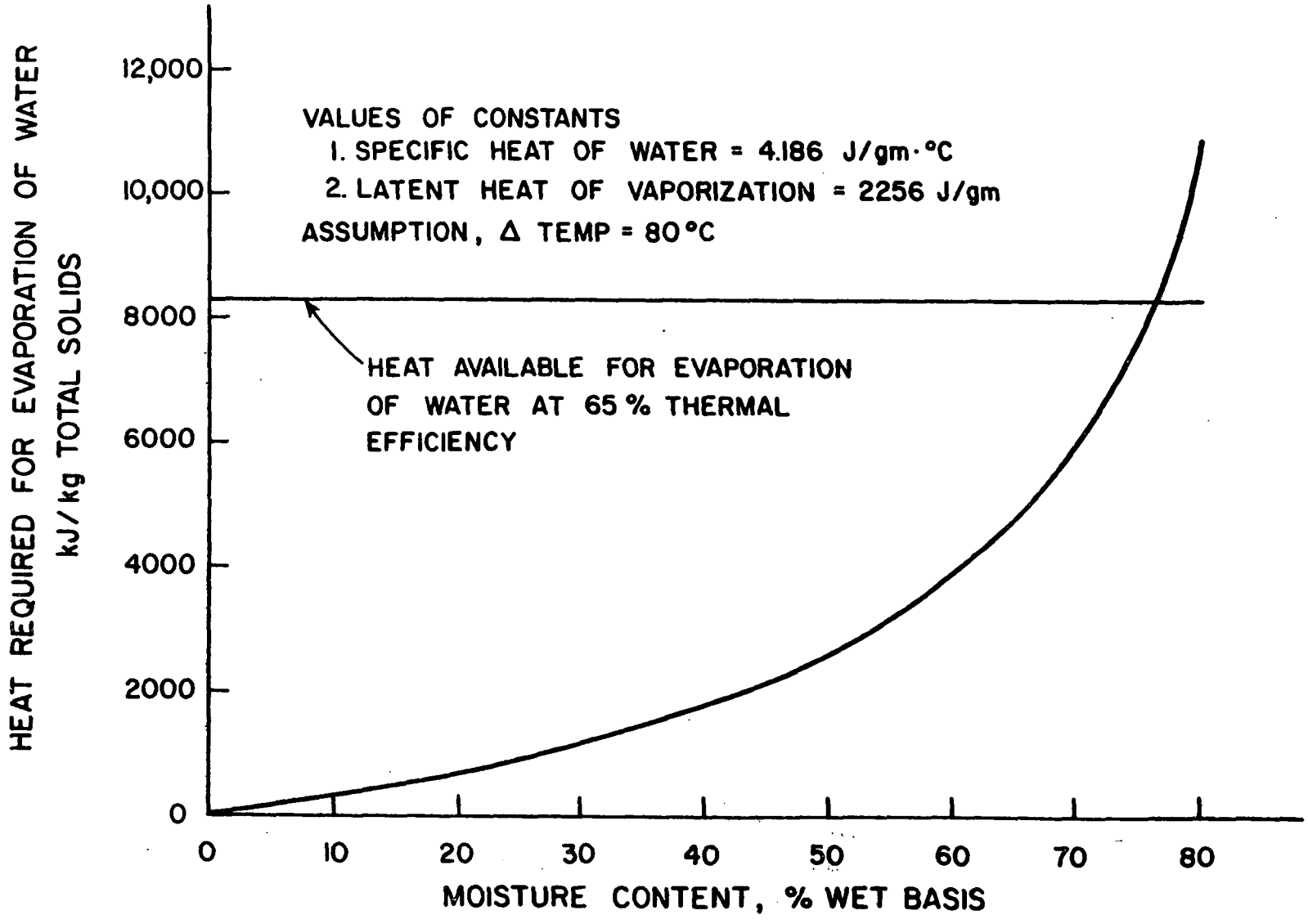

Figure 3. Relationship Between Moisture Content and Heat Required for Evaporation of Water in Comparison with the Heating Value of Cattle Manure.

As produced, the moisture content of livestock and poultry manures exceeds 75% wb. Thus, although manures are attractive as thermochemical process feedstocks on the basis of elemental analysis, they are unsuitable without drying or addition of low moisture content organic matter. Only manures produced in semi-arid and arid areas or manures which contain substantial quantities of bedding or litter materials such as broiler litter can be realistically considered as feedstocks for direct combustion, pyrolysis, or partial oxidation.

PLANT NUTRIENT LOSSES

A majority of the investigations that have evaluated the use of livestock and poultry manures as boiler fuels and feedstocks for other thermochemical processes were conducted during the late 1960's and early 1970's. During this time period, abundant supplies of low cost inorganic fertilizers were readily available, and the monetary value of manures as fertilizer materials often did not justify expenditures required for such utilization. Thus, losses of manurial plant nutrients associated with the thermochemical processes were of little concern and received little attention.

Prices for inorganic fertilizer materials (Figure 4) and therefore the monetary value of manures as fertilizer materials (Table 5) have increased substantially over the past decade. Thus, loss of plant nutrients when manures are utilized as fuels or thermochemical process feedstocks can translate into a significant opportunity cost if using manures as fertilizer materials is an available option. This section has two objectives. The first is to summarize the available information concerning losses of nitrogen, phosphorus, and potassium associated with combustion, pyrolysis, and partial oxidation. The second is to compare the opportunity cost of manurial plant nutrient losses to the value of energy produced.

TABLE 5. COMPARISON OF THE MONETARY VALUES* OF LIVESTOCK AND POULTRY MANURES BASED ON NITROGEN, PHOSPHORUS, AND POTASSIUM CONTENT †, $/TONNE OF DRY MATTER.

Year	Dairy Cow	Beef Feeder	Laying Hen	Broiler
1968	$13.18	$18.66	$19.57	$21.03
1974	$28.35	$42.23	$46.35	$47.38
1979	$31.25	$46.99	$50.88	$51.13

* Based on values presented in Figure 4.
† Agricultural Engineers Yearbook (1980)

Under the high temperatures common to combustion and other thermochemical processes, organic nitrogen is converted to ammonia. Subsequently,

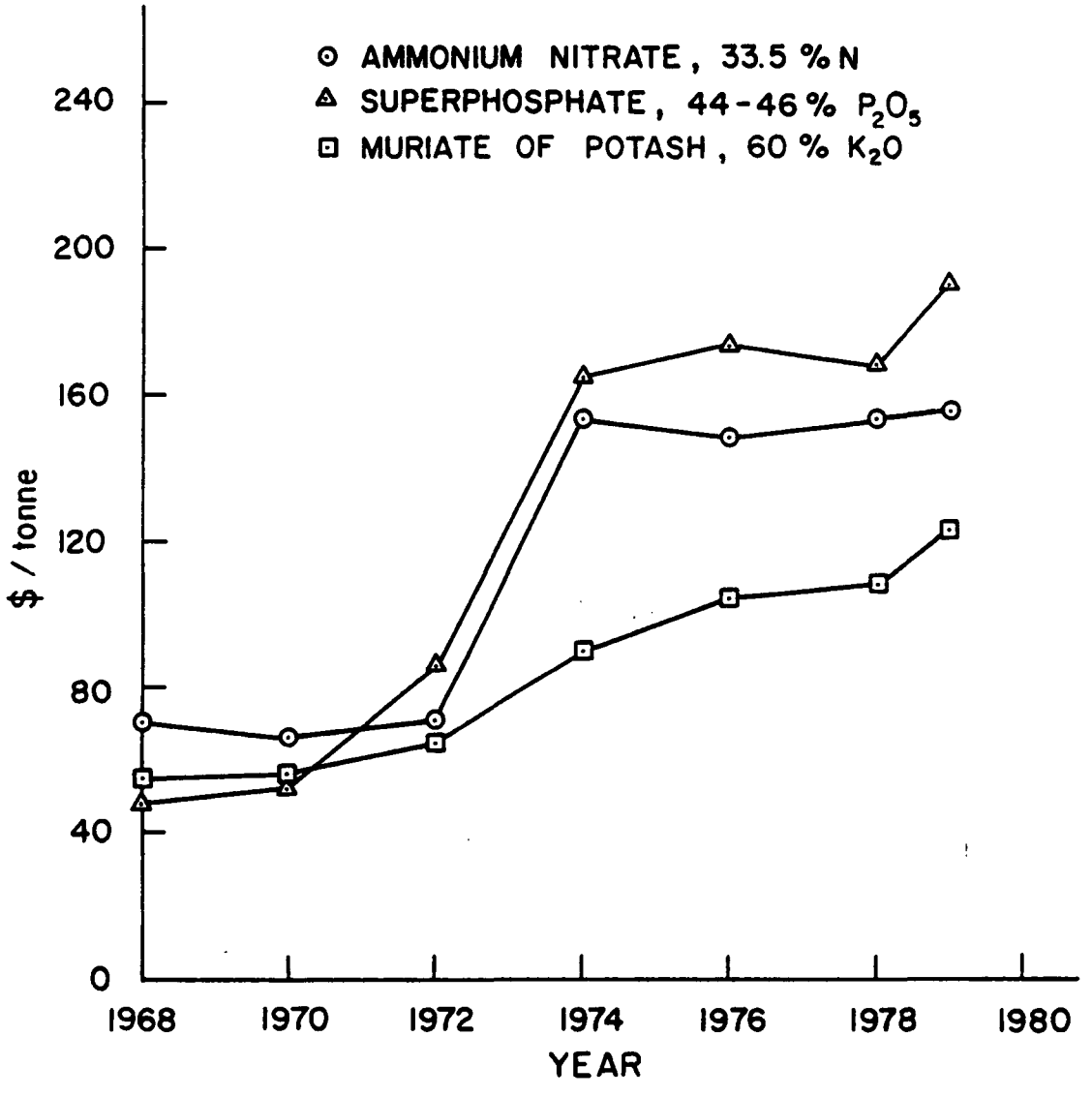

Figure 4. Average Prices Paid by U.S. Farmers for Fertilizer Materials, 1968-1979 (Agricultural Prices, 1969-1980).

ammonia molecules can be thermally cracked producing elemental nitrogen and hydrogen. When manures are used as boiler fuels, loss of nitrogen is essentially complete with both ammonia and elemental nitrogen becoming components of stack gases. For pyrolysis and partial oxidation, elemental nitrogen is a significant constituent of the gas produced; values from 15% to 40% of dry gas volume have been reported (White and Taiganides, 1971; Garner et al., 1972 and Huffman et al., 1978). Although this nitrogen can be recovered via ammonia synthesis, it will be lost during combustion.

Nelson (1973) reported significant concentrations of ammonia nitrogen in condensate and char produced when poultry manures were pyrolyzed. Reported values for condensate ammonia nitrogen concentration ranged from 42,000 mg/ℓ to 59,000 mg/ℓ and ranged from 2.6% to 3.8% by weight for chars. Dunn et al. (1976) reported that the aqueous fraction of condensate produced during pyrolysis of beef cattle manure contained less than 1% nitrogen. The nitrogen content of oil and tar and char fractions is a moot point, however, if energy production is the process objective since these residuals probably have greater value as fuels and the nitrogen present will ultimately be lost during combustion.

Although it is generally assumed that neither phosphorus nor potassium losses occur where manures are utilized in thermochemical processes, material balances to support this assumption are lacking. Mineral analyses of chars and ashes do suggest, however, that these materials are fairly concentrated sources of phosphorus and potassium as well as calcium and magnesium (Table 6). This has led to suggestions that residual chars and ashes have value as fertilizer materials (Davis et. al., 1972 and Khara et. al., 1975). It has been noted, however, that soluble salts such as sodium chloride which are harmful to plants are also concentrated in these chars and ashes (Nelson, 1973; Whetstone et. al., 1974; and Kreis, 1979). Thus, the value of these residuals as sources of phosphorus and potassium needs critical examination. In addition, the availability of the plant nutrients contained in these residuals remains undetermined.

TABLE 6. CONCENTRATIONS OF MINERALS PRESENT IN ASH AND CHAR RESIDUALS PRODUCED BY COMBUSTION, PYROLYSIS, AND PARTIAL OXIDATION OF POULTRY AND BEEF CATTLE MANURES.

	Poultry Manure*			Beef Cattle Manure†
Minerals	Combustion ash, 600°C	Low temperature (Brown) char, 482°C††	High temperature (Black) char, 815°C††	Partial oxidation ash
Phosphorus	11.4	10.9	8.4	---
Potassium	24.6	27.1	27.5	12.5 - 20.0
Calcium	10.8	11.8	9.4	4.3 - 4.9
Magnesium	2.8	3.0	2.4	---

* Nelson, 1973
† Khara et al. 1975
†† Samples combusted at 600°C prior to mineral analysis

Even though knowledge of the magnitude of plant nutrient losses that occur when manures are used as fuels and feedstocks for other thermochemical processes is imperfect, it is possible to illustrate the monetary significance of such losses. Table 7 presents such an illustration comparing the monetary value of manures used as replacements for conventional fuels with and without consideration of the opportunity costs associated with plant nutrient losses. As shown, using manures as sources of energy via thermochemical processes can involve a significant economic trade-off if opportunities for plant nutrient utilization exist. This is especially true if the use of coal is an available alternative for energy production.

TABLE 7. ILLUSTRATION OF THE IMPACT OF PLANT NUTRIENT LOSSES ON THE MONETARY VALUE OF MANURES USED TO REPLACE CONVENTIONAL FUELS.*

	Replacement of		
	Fuel Oil, No. 2†	Natural Gas††	Anthracite Coal§
Gross value, $/tonne of dry matter#	103.32	51.66	45.92
Net value, $/tonne of dry matter			
Dairy	72.07	20.41	14.67
Beef	56.33	4.67	-1.07
Laying Hen	52.44	0.78	-4.96
Broiler	52.19	0.33	-5.21

* Based on 1979 values presented in Table 5.
† $8.10/GJ
†† $4.05/GJ
§ $3.60/GJ
# $12.755 GJ/tonne

ENVIRONMENTAL QUALITY IMPACTS

Although the use of livestock and poultry manures as fuels and as feedstocks for other thermochemical processes has been considered in a number of studies, the possible environmental quality impacts have received little attention. Thus, a detailed analysis and comparison of possible impacts and benefits is not possible. However, the environmental quality impacts associated with the processes can be outlined based on knowledge of process fundamentals and the limited data base that is available.

The use of manures as boiler fuels will result in the production of potential air pollutants that are commonly associated with combustion such

as oxides of sulfur (SO_x) and nitrogen (NO_x), carbon monoxide, and particulates. Both sulfur dioxide (SO_2) and sulfur trioxide (SO_3) are of particular concern. SO_2 can damage plants and SO_3, which is hygroscopic, combines readily with water creating sulphuric acid.

The quantity of SO_x produced during combustion is determined by fuel sulfur content. When compared to conventional fuels (Table 8), beef feedlot manure contains more sulfur on a mg/kJ basis than most conventional fuels including low sulfur (anthracite) coal. Although data are not available, it is probable that other manures are comparable in sulfur content. However, the need for control of SO_x emissions to meet ambient air quality standards when animal manures are used as boiler fuels as suggested by Sweeten (1980) is unclear. The need for control of SO_x emissions appears unlikely, however, as the use of manures as boiler fuels will most probably be limited to rural areas.

TABLE 8. COMPARISON OF THE SULFUR CONTENT OF BEEF CATTLE FEEDLOT MANURE AND CONVENTIONAL FUELS.

Fuel	Sulfur, % as S by wt	Sulfur, mg/kJ
Anthracite coal*	0.8	0.27
High volatile B bitumenous coal*	2.8	1.03
Fuel oil, mid-continent*	0.35	0.08
Fuel oil, California*	1.16	0.26
Pipeline natural gas*	Tr†	Tr†
Municipal sewage sludge solids ††	0.70	0.40
Beef cattle feedlot manure §	0.77	0.55
Beef cattle feedlot manure #	0.80	0.59

* Schlesinger et al., 1978
† Tr = trace
†† Ballou et al., 1980
§ Sweeten and Higgins, 1980
# Engler et al., 1975

The formation of nitrogen oxides during combustion results from the oxidation of atmospheric nitrogen and varies with equipment design and operating conditions. It appears, however, that nitrogen present in fuels, particularly as ammonia, can contribute to the formation of nitrogen oxides. For conventional fuels such as coal and fuel oil, nitrogen content is minimal (Table 9) and contribution to nitrogen oxide formation during combustion is of little concern. The nitrogen contents of animal manures and sewage sludge solids are substantially higher than those of conventional fuels. Thus, there is the possibility of increased nitrogen oxide emissions when manures are used in place of conventional boiler fuels.

TABLE 9. COMPARISON OF THE NITROGEN CONTENT OF MANURES AND CONVENTIONAL FUELS.

Fuel	Nitrogen, % as N by wt	Nitrogen, mg N/kJ
Anthracite coal*	0.8	0.27
High volatile B bitumenous coal*	2.8	0.48
Fuel oil, mid-continent*	0.5	0.11
Municipal sewage sludge solids†	4.5	2.68
Beef feeder manure††	4.9	2.88
Dairy cow manure††	3.9	2.29
Laying hen manure††	5.4	3.18
Broiler manure††	6.8	4.00

* Schlesinger et al., (1978)
† Ballou et al., (1980)
†† Agricultural Engineers Yearbook (1980)

As discussed earlier, solids, liquids, and gases are produced when organic materials such as manures undergo pyrolysis or partial oxidation. Since closed reactors are used for these processes, any possible environmental quality impacts will be associated with the utilization or disposal of the products produced. Available data (Table 10) suggests that both the fuel gas and char produced by pyrolysis or partial oxidation of manures are attractive as fuels due to their low sulfur content. However, the relationship between feedstock sulfur content and the quantities of sulfur present in the gases and chars remains undefined as does the sulfur content of the oils and tars produced.

TABLE 10. COMPOSITION OF FUEL GASES AND CHARS PRODUCED FROM MANURE BY PYROLYSIS AND PARTIAL OXIDATION.

	Batch Pyrolysis		Partial Oxidation	
	A	B	C	D
Gas composition, % volume basis				
Oxygen	0.0	4	0.3-2.5	0.0
Nitrogen	0.0	19	28.4-38.3	7.1
Carbon Dioxide	24.5	18	13.1-18.7	14.2
Carbon Monoxide	18.0	18	11.5-17.3	12.8
Hydrogen	27.5	30	18.1-26.2	27.4
Methane	22.7	--	6.2-7.9	32.3
Ethylene	0.0	13†	2.7-4.1	5.9
Ethane	0.0	--	0.3	0.0
Hydrogen Sulfide	0.0	0.0	0.0	0.0
Char composition, % weight basis				
Carbon	49.4	63	32.0-41.2	*
Hydrogen	0.4	*	0.3-1.6	*
Oxygen	0.4	*	*	*
Nitrogen	1.1	*	2.0-2.5	*
Sulfur	0.3	*	*	*

A. Schlesinger et al., 1972
B. White and Taiganides, 1971
C. Halligan et al., 1974
D. Huffman et al., 1978

* Not reported
† Combustibles and illuminants

As shown in Table 10, the nitrogen content of the chars and fuel gases produced during pyrolysis and partial oxidation of manures is variable. Consequently, there will be the possiblility of nitrogen oxide emissions when these materials are used as fuels. Fuel gases produced via partial oxidation should contain larger quantities of nitrogen oxides as compared to gases produced by pyrolysis since limited quantities of air are limited to support controlled combustion with partial oxidation.

As noted in Table 3 and also by Nelson (1973), significant quantities of water, as much as 478 ℓ per tonne of manurial dry matter, are produced during pyrolysis even when low moisture content feedstock is used. The same is true for partial oxidation. These wastewaters appear similar to those produced during the conversion of coal to coke containing high concentra-

tions of ammonia nitrogen (Cousins and Mindler, 1972). As noted earlier, Nelson (1973) reported condensates produced during pyrolysis of laying hen manure contained ammonia nitrogen concentrations ranging from 42,000 mg/ℓ to 59,000 mg/ℓ. This waste stream could be a serious liability if land application to utilize the nitrogen present is not an available option.

Possible environmental quality problems related to disposal of ash produced during combustion of manure or char also have received little attention beyond recognition of possible problems associated with concentration of salts. If land disposal is practiced, it has been suggested that land requirements would be comparable to those for disposal of the original quantity of manure (Kreis, 1979). Thus, one of the apparent advantages of these processes, reduction in land requirements for manure disposal, is negated. The alternative of landfilling presents possible groundwater contamination problems.

SUMMARY AND CONCLUSIONS

Analysis of the limited information that is available suggests that use of either combustion, pyrolysis or partial oxidation for the recovery of usable forms of energy from livestock and poultry manures is not overly attractive. All three processes require low moisture content feedstocks to achieve reasonable levels of thermal efficiency (Figure 3). Although a detailed comparison of thermal efficiencies, i.e., feedstock energy produced to energy available of the ultimate point of use, was not possible, it appears that direct combustion is the most desirable of the three processes in situations where low moisture content manures are available. The comparatively low overall thermal efficiencies of pyrolysis and partial oxidation (Table 3) are compounded when the thermal efficiences associated with the ultimate use of the fuels produced also are considered.

The use of manures directly as fuels or as feedstocks for pyrolysis and partial oxidation can involve significant opportunity costs if options for utilizing manurial nitrogen, phosphorus, and potassium are available. The value of phosphorus and potassium contained in char and ash fractions is unclear due to the concentration of salts that can be harmful to plants.

Possible adverse environmental quality impacts associated with using animal manures as fuels and feedstocks for pyrolysis and partial oxidation have received little attention. It appears, however, that the potential for adverse impacts exists but sufficient data to assess the possible significance is lacking. Of particular concern are the possible impacts of: a) the wastewater generated during pyrolysis and partial oxidation, b) char and ash disposal, and c) sulfur and nitrogen oxides in the gases that are produced.

One aspect of using combustion, pyrolysis, and partial oxidation to produce usable forms of energy from animal manures not discussed in this section is economic feasibility. This omission was not accidental. Although there have been several estimates of capital and operating costs, there has been little agreement between estimates due to differences in assumptions. This results from the lack of any full scale or even significant pilot plant scale experience with these processes and manures.

This study initially attempted to develop a rational basis for ranking combustion, pyrolysis, and partial oxidation as processes for recovering usable forms of energy from animal manures. The criteria to be used included material and energy balances as well as costs. However, this information was not available. It appears, however, that combustion, using manures directly as fuels, is the most desirable of the three processes. This conclusion is based on the following: (1) process simplicity, (2) apparently greater thermal efficiency, and (3) absence of a liquid waste stream. The above conclusion is in agreement with that reached by Whetsone et al., (1974) in an earlier analysis of this subject area.

SECTION 4

ANAEROBIC DIGESTION

In recent years, there has been growing interest in the U.S. in the possibility of using anaerobic digestion to produce usable energy from livestock and poultry manures. This topic has been the subject of several extensive studies. Although these studies have demonstrated the technical feasibility of manurial biogas production, economic feasibility in the U.S. remains unclear. This section:

1. Reviews the history of anaerobic digestion as a unit process, discusses process fundamentals, and summarizes the results of manurial biogas production research.

2. Examines the economic feasibility of manurial biogas production based on estimates of production costs and biogas utilization options.

3. Considers possible environmental quality implications of manurial biogas production.

HISTORICAL BACKGROUND

It has been known for more than a century that a flammable gas, now commonly called biogas, is produced when organic materials decompose in the absence of oxygen. Although the concept of using anaerobic digestion to produce energy is not new, this process has been utilized only to a very limited extent solely as an energy producing process. It is, however, used extensively for the stabilization of wastes, particularly wastewater sludges. The following briefly reviews the history of anaerobic digestion as a process for waste stabilization and energy production particularly from animal manures.

Credit for first recognizing the potential of anaerobic digestion as a waste stabilization process is generally given to Louis Mouras (McCabe and Eckenfelder, 1958; Griffiths, 1960). Around 1860, Mouras, a Frenchman, received a patent for a sealed cesspool known as the Mouras automatic scavenger. This tank was used to liquify wastes from several households prior to discharge to a sewer.

It appears that the potential for using the combustible gas produced during the liquification of wastewater solids was first recognized by an Englishman, Donald Cameron (Metcalf and Eddy, 1935). In 1895, Cameron

designed and constructed the first septic tank for the city of Exeter, England and used the gas produced for street lighting.

In the early 1900's, several different types of dual purpose tanks that combined sedimentation and anaerobic digestion of wastewater solids were developed. Examples include the Travis hydrolytic tank, the Biolytic tank and the Imhoff tank. Imhoff tanks were widely used, particularly in Germany and the U.S. (Grifiths, 1960). Use of separate tanks for the digestion of wastewater solids also began during this period. In 1911, the first separate tanks for anaerobic digestion in the U.S. were constructed at the wastewater treatment plant in Baltimore, Maryland (Wagenhals et al., 1925). Since the 1920's, the anaerobic digestion process has been studied extensively. Among the more significant results of these studies have been major improvements in digestion tank design and the use of heat to accelerate the digestion process.

Recognition of the potential of using anaerobic digestion to produce usable energy from animal manures also dates back to the 1800's. Results of a student's experiments produced the observation by Pasteur that anaerobic digestion might be used to produce biogas from animal manures for heating and illumination (Tietjen, 1975). In the 1930's, Buswell and others conducted a number of comprehensive studies on this topic (Buswell and Boruff, 1933; Jacobs, 1934; Buswell and Hatfield, 1936). Studies of manurial biogas production also began in India in the late 1930's (National Academy of Sciences, 1977).

A number of manurial biogas plants were built on farms in France, Germany, and Algeria in response to war-related disruptions in supplies of conventional fuels during and immediately after World War II (Tietjen, 1975). Many of these plants were quickly abandoned, however, as supplies of conventional fuels were reestablished. In 1976, only one of the more than 1000 digesters built in France and Germany for the production of manurial biogas was known to be in operation (Jewell et al., 1976).

Although manurial biogas production received little attention in the U.S. and Europe in the years following World War II, the research program iniated in India in the late 1930's was continued and expanded (National Academy of Sciences, 1977). This research program has led to the construction of several thousand small-scale manurial biogas plants to provide fuel for cooking and illumination in rural areas of India. Construction of numerous manurial biogas plants also has occurred in the People's Republic of China, Korea, and Taiwan.

A renewal of interest in the anaerobic digestion of animal manures occurred in the United States beginning in the early 1960's (Hart, 1963; Cassell and Anthonisen, 1966; and Gramms et al., 1971). Emphasis was on waste stabilization, however, with energy production a very secondary concern. This reflected the environmental concerns and low energy costs of the period. Although it was demonstrated that anaerobic digestion could be an effective process for stabilizing animal manures, there was little interest due to high costs which were not adequately offset by the value of the biogas produced.

With the oil embargo of 1973 and subsequent increases in crude oil prices acting as catalysts, the concept of manurial biogas production became the subject of renewed interest in the U.S. in the mid-1970's. Since 1975, several full scale, experimental systems for manurial biogas production have been constructed and operated for extended periods of time. Examples include digesters located at Cornell University, The Pennsylvania State University, University of Missouri, Washington State Reformatory Dairy Farm, and U.S. Meat Animal Research Center. Results from these studies are discussed elsewhere in this report.

PROCESS FUNDAMENTALS

Anaerobic digestion is a microbial process in which complex organic compounds are degraded in the absence of oxygen producing biogas and other reduced compounds as end products. Methane (CH_4) and carbon dioxide (CO_2) are the principal constituents of biogas with methane generally constituting between 50% and 70% of the gas produced. The other 30% to 50% is primarily carbon dioxide. Hydrogen (H_2), hydrogen sulfide (H_2S), ammonia (NH_3), nitrogen (N_2), and water vapor also can be constituents of biogas but are normally present only in trace amounts.

The microbial conversion of organic carbon to biogas traditionally has been viewed as a two-step process involving two distinct groups of bacteria (Metcalf and Eddy, Inc., 1979). The first step of the two-step process scheme (Figure 5) usually is described as the acid phase. In this phase, complex organic compounds; carbohydrates such as sugars, starches, cellulose, and hemicellulose; proteins; and lipids (fats) are hydrolyzed and fermented. The resultant compounds that can be utilized subsequently for methane production include:

A) Fatty acids containing a maximum of six carbon atoms (formic, acetic, propionic, butyric, valeric, and caproic acids).

B) Normal and isoalcohols containing from one to five carbon atoms (methanol, ethanol, propanol, butanol, and pentanol).

C) Inorganic gases (hydrogen, carbon monoxide, and carbon dioxide).

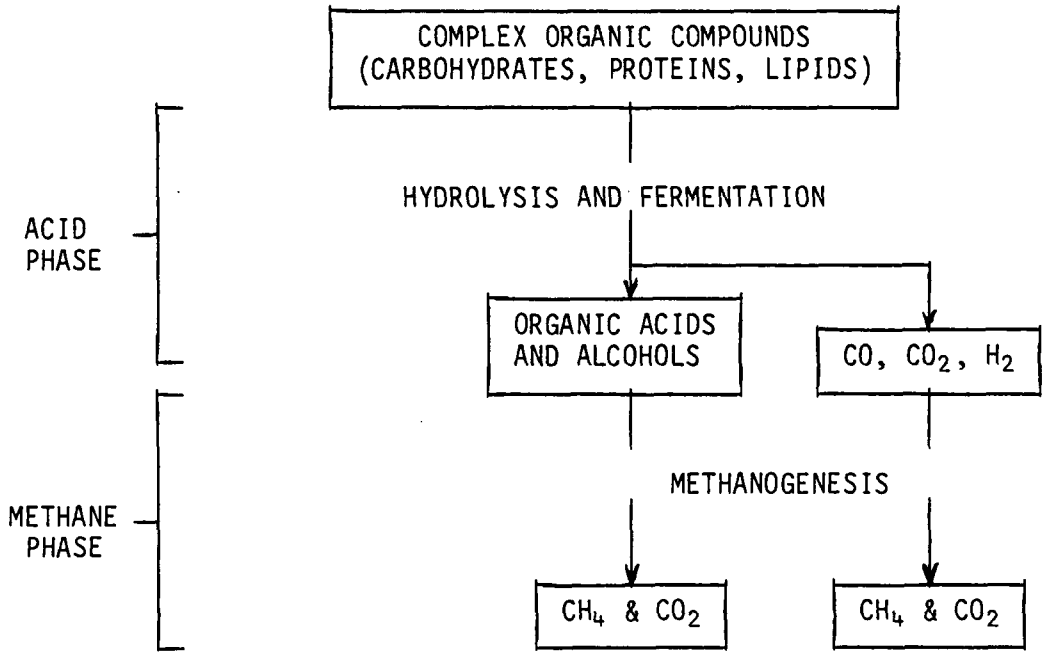

Figure 5. General schematic for the two-step conceptualization of the anaerobic digestion process.

Collectively, the microorganisms associated with the first step of the anaerobic digestion process are known as "acid formers." Included in this group are facultative and obligate anaerobic bacteria capable of producing proteolytic, lipolytic, ureolytic, or cellulytic enzymes.

In the second step of the two-step process scheme, the products of hydrolysis and fermentation are converted to methane and carbon dioxide. The formation of methane from substrates such as ethanol, butyrate, and hydrogen involves substrate oxidation and reduction of atmospheric carbon dioxide as illustrated by the following equations:

$$2\ C_2H_5OH + CO_2 \text{ ---> } 2\ CH_3COOH + CH_4 \qquad (1)$$

$$4\ H_2 + CO_2 \text{ ---> } CH_4 + 2\ H_2O \qquad (2)$$

For substrates such as acetic and propionic acids, methane is formed by reduction of carbon dioxide that was formed during substrate oxidation as illustrated by the following equations:

$$4\ C_2H_5COOH + 8\ H_2O \text{ ---> } 4\ CH_3COOH + 4\ CO_2 + 24\ H \qquad (3)$$

$$3\ CO_2 + 24\ H \text{ ---> } 4\ CH_4 + 6\ H_2O \qquad (4)$$

$$4\ C_2H_5COOH + 2\ H_2O \text{ ---> } 4\ CH_3COOH + CO_2 + 3\ CH_4 \qquad (5)$$

$$CH_3\ COOH \dashrightarrow CH_4 + CO_2 \qquad (6)$$

The principal genera of bacteria responsible for methane production are Methanobacterium, Methanobacillus, Methanococcus, and Methanoscarcinia (Higgins and Burns, 1975). Although methane can be produced from a number of compounds, most of the methane produced during the anaerobic digestion of complex organic materials such as manures is derived from the methyl group of acetate (McInerney and Bryant, 1980).

Recently, it has been suggested that anaerobic digestion may be more accurately described as a three-step process involving three and possibly four distinct groups of bacteria (McInerney and Bryant, 1980). This scheme is shown in Figure 6. The principal difference between this and the two-step conceptualization of the anaerobic digestion process is the identification of the fermentation of organic acids and alcohols to acetate, carbon dioxide, and hydrogen as a separate step. The production of acetate and possibly other acids from hydrogen and carbon dioxide also may be considered a separate step as indicated in Figure 6.

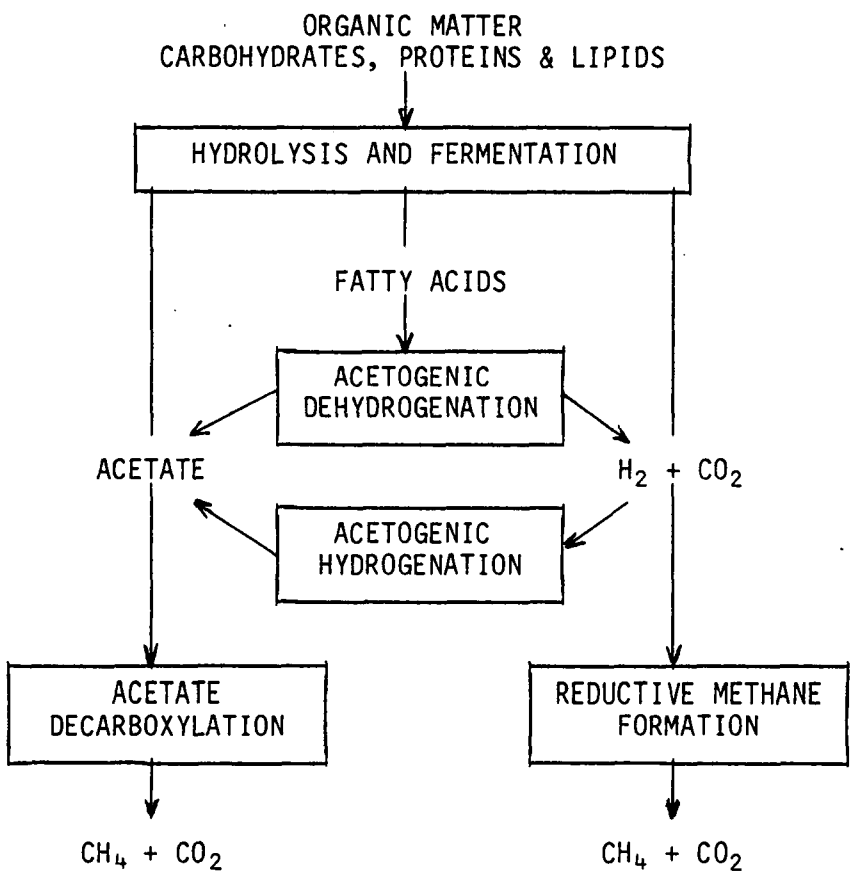

Figure 6. General schematic for the three-step conceptualization of the anaerobic digestion process (McInerney and Byrant, 1980).

Although the previous discussion has focused on carbon transformations, other transformations also occur during anaerobic digestion. As shown in Figures 5 and 6, proteins are utilized as substrates by the acid forming or fermentative group of bacteria. Proteins are first hydrolyzed producing constituent amino acids which are subsequently deaminated yielding ammonium ions and an α-Keto acid. The α-Keto acid is then transformed into acetic acid and subsequently to methane. The ammonium ions not utilized to satisfy microbial nutrient requirements generally remain in solution. For highly nitrogenous wastes such as animal manures, residual ammonia concentrations can be substantial and desorption of ammonia can occur if pH levels result in a significant concentration of unionized or free ammonia. Thus, ammonia can be a trace consituent of biogas.

Microbial transformations of phosphorus also occur during anaerobic digestion. During hydrolysis, organically bound phosphorus is transformed into inorganic forms such as orthophosphates. Inorganic phosphates are soluble compounds that can be utilized to satisfy microbial nutrient requirements. Excess inorganic phosphates remain in solution and are discharged with the stabilized waste.

The microbial formation of sulfides, particularly hydrogen sulfide (H_2S), during anaerobic digestion also is of importance. Sulfur is a constituent of certain amino acids and is released as sulfate (SO_4^{-2}) when these sulfur amino acids are hydrolyzed. The sulfate ion is then reduced to sulfide (S^{-2}) by Desulfovibrio and subsequently to hydrogen sulfide (H_2S). Since hydrogen sulfide is only slightly soluble in water, it becomes a constitutent of biogas.

SUMMARY OF RESEARCH RESULTS

The production of biogas from livestock and poultry manures has been the subject of a number of laboratory, pilot-plant, and full scale studies. Tables 11 through 14 summarize the results from several of the more comprehensive studies that have been conducted. These studies not only have demonstrated that manurial biogas production is technically feasible but also have provided a rational basis for system design and operation by delineating relationships between parameters such as loading rate and detention time and process performance. Examples of these relationships are presented in Figures 7 through 12.

Table 15 presents biogas production estimates for typical livestock and poultry enterprises. Based on maximum reported values for biogas production on a m^3/kg VS added basis (Tables 11 through 14). As shown, the gross amount of energy that could be produced is appreciable. It should be recognized that biogas available for utilization will be less, perhaps significantly less due to digester heating requirements, than the estimates presented and will vary with system design, method of operation, and climatic conditions. It also should be recognized that it may not be economically desirable to maximize biogas production due to the reactor volume necessary.

TABLE 11. BIOGAS PRODUCTION FROM DAIRY MANURE-RESEARCH RESULTS.

Source	Loading Rate, KG VS*/m^3-day	Detention Time, Days	VS* Reduction, %	Gas Production, m^3/KG VS* added	Gas Production, m^3/KG VS* removed	Gas Composition, % CH_4	Temp., °C
Morris, 1976†	15.21	5	18.8	0.12	0.63	61	32.5
	7.60	10	29.0	0.25	0.87	64	32.5
	3.80	20	35.1	0.32	0.92	63	32.5
	2.55	30	37.6	0.36	0.95	63	32.5
Pigg, 1977	5.1	10	--	0.22	--	54	35
	3.9	15	--	0.29	--	54	35
	3.0	20	--	0.34	--	54	35
	2.2	30	--	0.39	--	54	35
Converse et al., 1977	6.22	10.4	29.4	0.27	0.87	57	35
	10.51	6.2	27.9	0.25	0.86	54	60
Jewell et al., 1980	11.05	10	26.2	0.20	0.78	60	35
	7.50	15	27.8	0.28	1.00	55	35
	3.19	30	31.7	0.31	0.98	58	35
	11.05	10	30.2	0.23	0.77	60	35
	7.50	15	34.1	0.33	0.99	55	35
	3.19	30	40.6	0.36	0.89	57	35

*Volatile solids

TABLE 12. BIOGAS PRODUCTION FROM LAYING HEN MANURE-RESEARCH RESULTS.

Source	Loading Rate, KG VS*/m^3-day	Detention Time, Days	VS* Reduction, %	Gas Production, m^3/KG VS* added	Gas Production, m^3/KG VS* removed	Gas Composition, % CH_4	Temp., °C
Gramms et al. 1971	1.9	10	67	0.30	0.45	58	32.5
	1.9	15	67	0.36	0.53	58	32.5
	3.8	10	64	0.25	0.48	53	32.5
	3.8	15	57	0.28	0.49	52	32.5
Converse et al., 1981	1.80	36	62	0.37	0.60	58	35
	1.65	46	56	0.44	0.79	61	35
	1.85	45	56	0.44	0.79	63	35
	2.14	38	51	0.46	0.90	63	35
	2.29	36	65	0.51	0.78	64	35

*Volatile solids

TABLE 13. BIOGAS PRODUCTION FROM SWINE MANURE-RESEARCH RESULTS.

Source	Loading Rate, KG VS*/m^3-day	Detention Time, Days	VS* Reduction, %	Gas Production, m^3/KG VS* added	Gas Production, m^3/KG VS* removed	Gas Composition, % CH_4	Temp., °C
Gramms et al. 1971	1.9	10	52	0.25	0.49	61	32.5
	1.9	15	61	0.42	0.69	60	32.5
	3.8	10	44	0.36	0.83	58	32.5
	3.8	15	59	0.43	0.73	59	32.5
Kroeker et al., 1975	1.0	30	44	0.76	1.74	67	35
	2.1	15	36	0.65	1.90	68	35
Fischer et al., 1979	4.0	15	63	0.58	1.10	59	35

*Volatile solids

TABLE 14. BIOGAS PRODUCTION FROM BEEF CATTLE MANURE-RESEARCH RESULTS.

Source	Loading Rate, KG VS*/m^3-day	Detention Time, Days	VS* Reduction, %	Gas Production, m^3/KG VS* added	Gas Production, m^3/KG VS* removed	Gas Composition, % CH_4	Temp., °C
Loehr and Agnew, 1967	1.35	10	58.6	0.56	0.96	58	35
	2.71	10	45.3	0.55	1.21	57	35
	3.51	10	34.4	0.74	2.15	52	35
	4.80	10	44.6	0.70	1.57	53	35
Hashimoto, et al., 1978	14.88	4	39.8	0.42	1.06	50	55
	11.45	6	46.1	0.43	0.94	53	55
	5.15	12	52.8	0.56	1.06	55	55
	3.42†	20	44.2	0.38	0.86	58	55

*Volatile solids

†No mechanical mixing

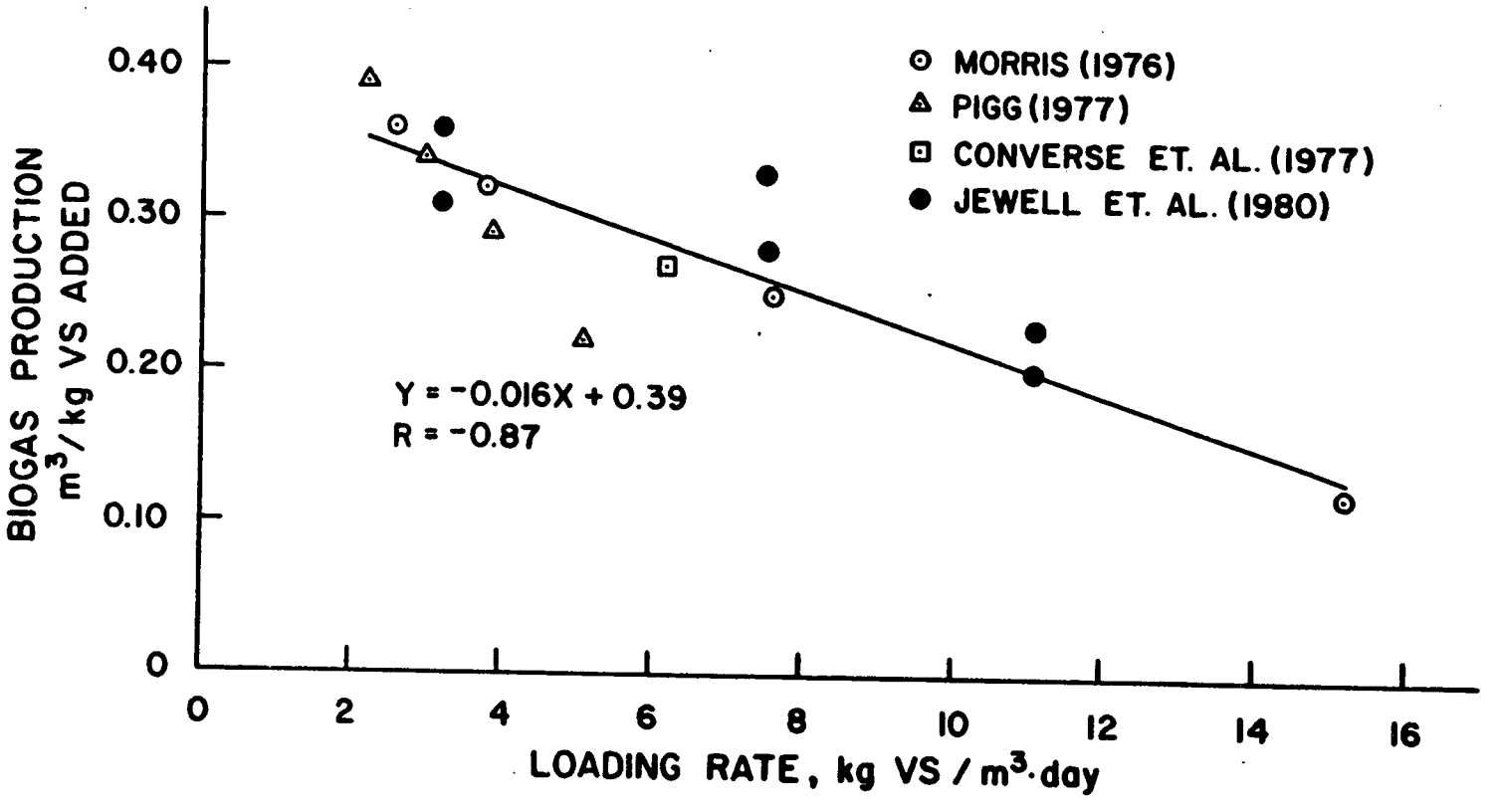

Figure 7. Relationship Between Biogas Production and Loading Rate for Dairy Manure, 35°C.

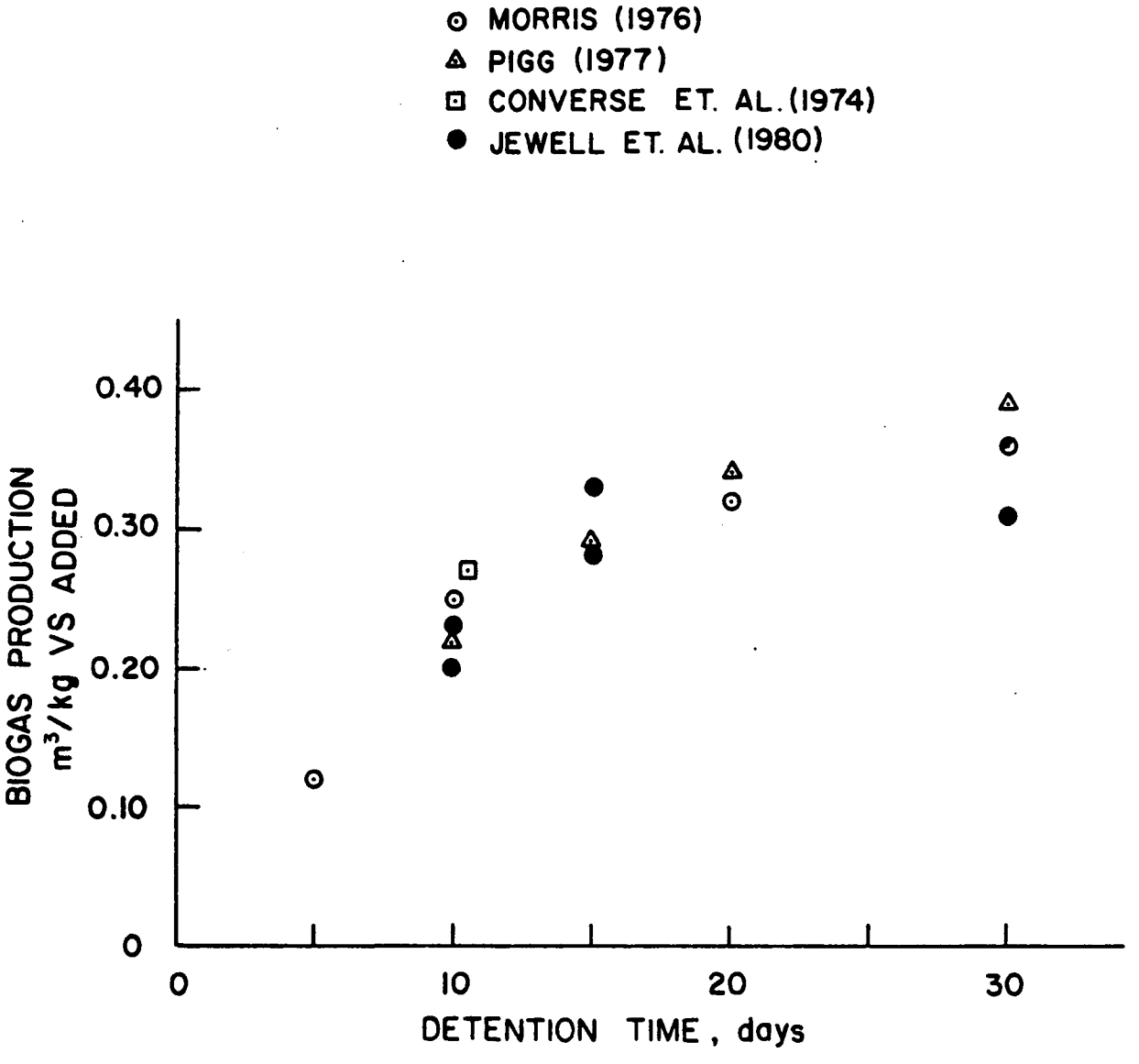

Figure 8. Effect of Detention Time on Dairy Manure Biogas Production, 35°C.

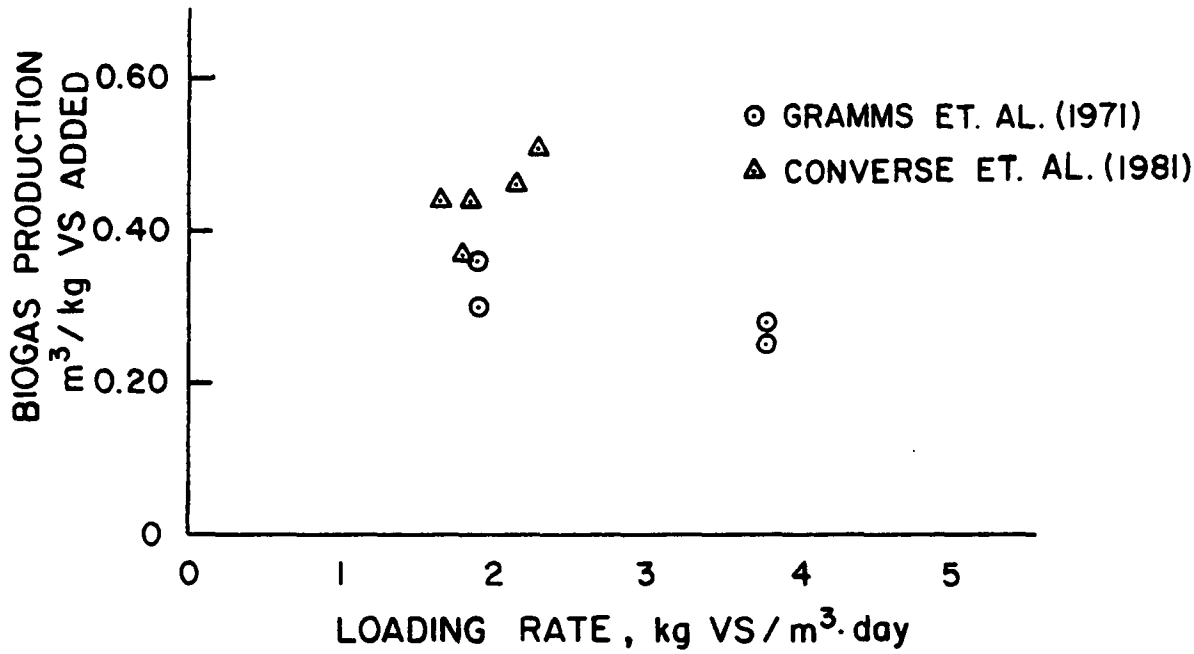

Figure 9. Relationship Between Biogas Production and Loading Rate for Laying Hen Manure, 35°C.

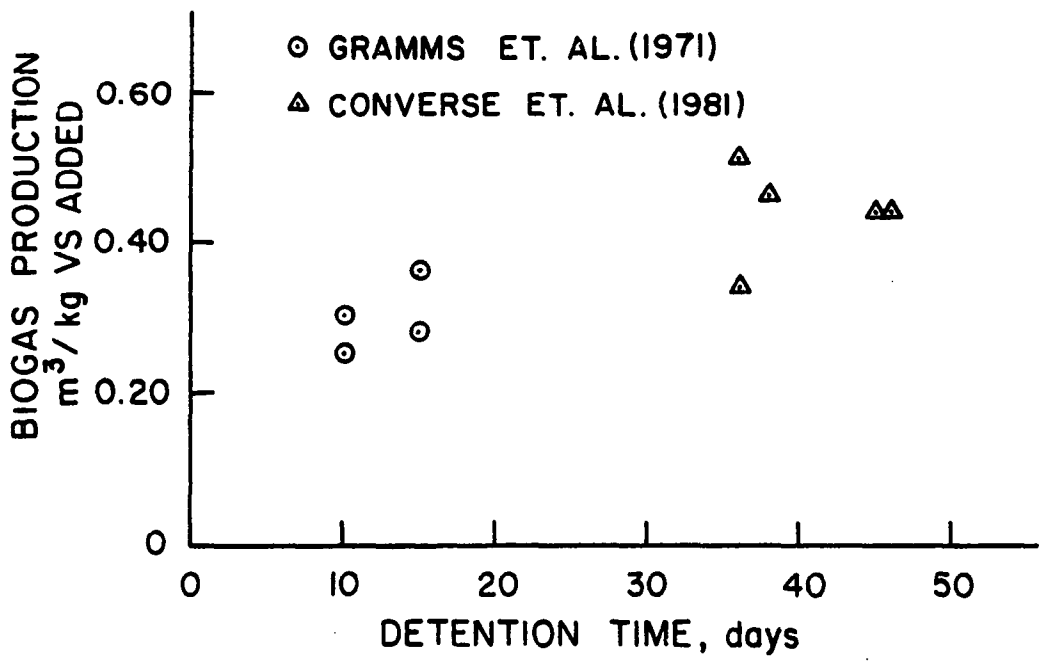

Figure 10. Effect of Detention Time on Laying Hen Manure Biogas Production, 35°C.

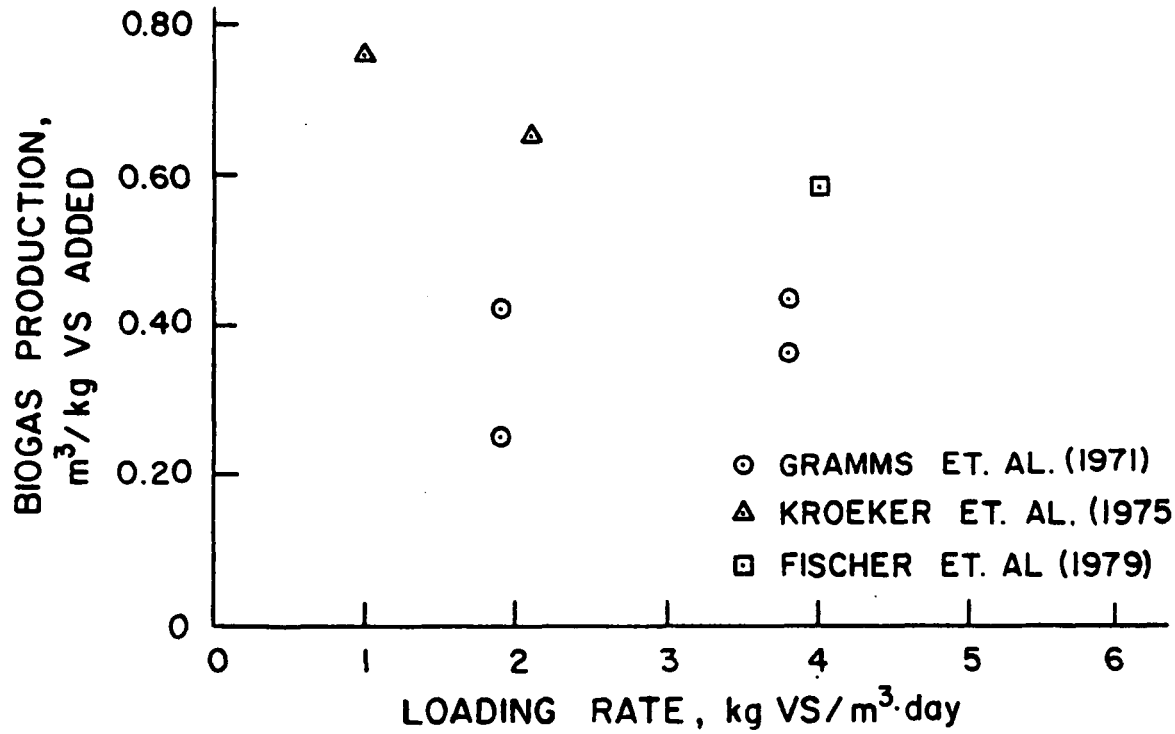

Figure 11. Relationship Between Biogas Production and Loading Rate for Swine Manure, 35°C.

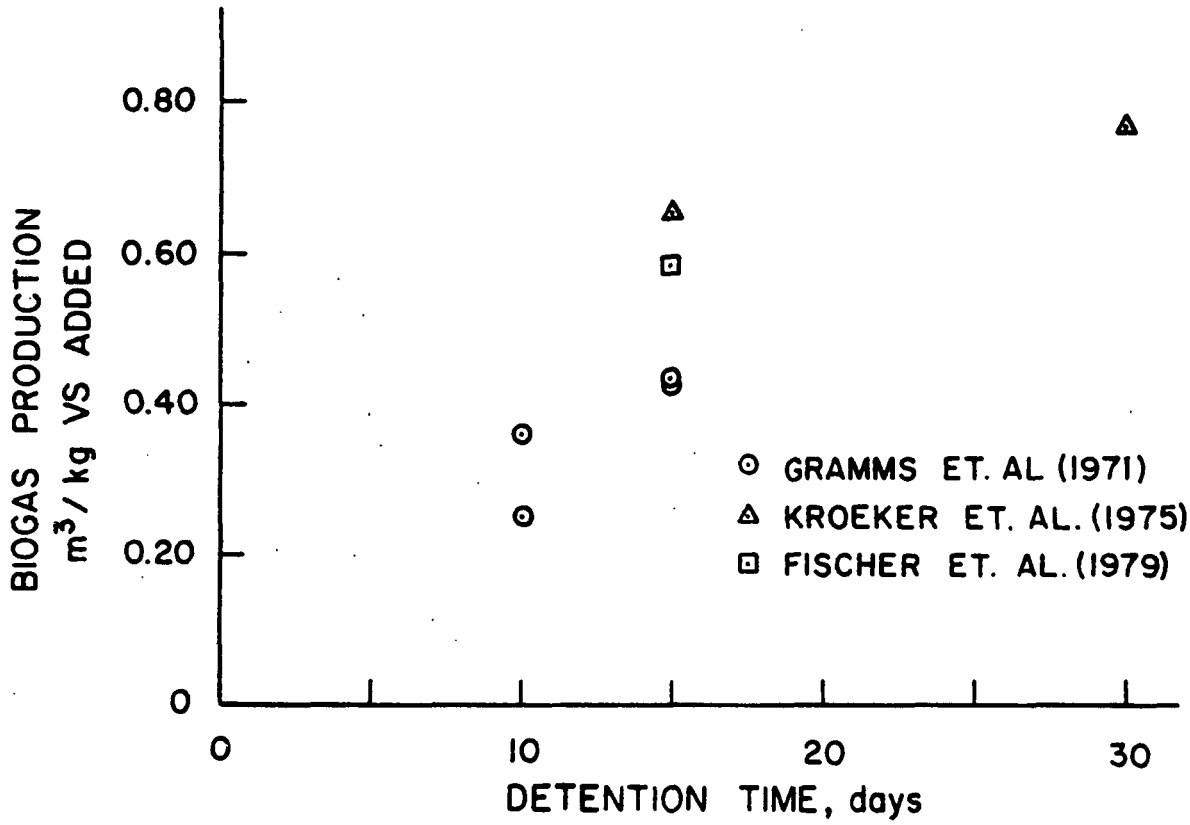

Figure 12. Effect of Detention Time on Swine Manure Biogas Production, 35°C.

TABLE 15. ILLUSTRATION OF BIOGAS PRODUCTION POTENTIAL FOR TYPICAL LIVESTOCK AND POULTRY PRODUCTION UNITS.

	Number of Animals	Volatile Solids Produced, kg/day*	Loading Rate, kg VS/m^3-day	Biogas Production, m^3/KG VS added	Biogas Production, m^3/Day	Gas Composition, % CH_4	Energy Produced, MJ/Day
Dairy cow, @ 545 KG	100	468	2.2†	0.39†	182	54	3,640
Beef Feeder, @ 363 KG	1,000	2,143	3.51††	0.74††	1,586	52	30,500
Swine Feeder, @ 64 KG	1,500	458	1.0§	0.76§	348	67	8,630
Laying Hen, @ 2 KG	30,000	570	2.29#	0.51#	291	64	6,890

*Agricultural Engineers Yearbook, 1980.

†Pigg, 1977.

††Loehr and Agnew, 1967.

§Kroeker et al., 1975.

#Converse et al., 1981.

ECONOMIC FEASIBILITY

Although it has been established that substantial quantities of energy in the form of biogas can be obtained from livestock and poultry manures, the economic feasibility of manurial biogas production is questionable. Assuming that alternative sources of energy are available, adequate income must be produced to provide an attractive rate of return for invested capital and management. Otherwise, other investment opportunities will be more attractive. The following sumarizes estimates of biogas production costs and examines biogas utilization and by-production recovery options as sources of income to offset costs and provide the returns necessary for the economic feasibility of this technology.

Biogas Production Costs

Even though the subject of manurial biogas production has been studied extensively, utilization of this technology under commercial conditions is just beginning to occur. Thus, opportunities for detailed analyses to determine production costs have been lacking. However, there have been several attempts to estimate the cost of producing biogas from dairy and beef cattle manures using information obtained from research studies. The results of these estimates are summarized and compared in Tables 16 and 17. Estimated production costs for electricity include costs associated with engine-generator set operation and are based on the assumption that waste engine heat is used to satisfy digester heating requirements. Thus, biogas production cost estimates which are components of the electricity production cost estimates are based on total rather than net biogas production. When compared to current (1981) prices for conventional sources of energy (Table 18), it appears that manurial biogas can be produced at a cost that is competitive with conventional fuels particularly fuel oil and liquified petroleum gas and also electricity.

TABLE 16. COMPARISON OF ESTIMATES OF THE COST OF PRODUCING BIOGAS FROM DAIRY CATTLE MANURE.

Source	No. of Animals	Production Cost	
		Biogas, $/GJ net	Electricity, $/kWh
Abeles et al. (1978)*	100	7.22	0.320
Coppinger et al. (1979)†	200	4.26	0.045
	400	3.23	0.036
Persson et al. (1979)†	100	4.96††	---
Jewell et al. (1980)*	50	4.38	---
	100	3.07	---
	300	2.13	---
	500	1.89	---
Jewell et al. (1980)†	150	9.00	---
	100	6.00	---
	300	4.00	---

*Earth supported, plug flow digester
†Conventional type, rigid wall digester
††Does not include labor costs

TABLE 17. COMPARISON OF ESTIMATES OF THE COST OF PRODUCING BIOGAS FROM BEEF CATTLE MANURE.

Source	No. of Animals	Production Cost	
		Biogas, $/GJ net	Electricity, $/kWh
Hashimoto et al. (1978)	10,000	6.33	---
Lizdas et al. (1980	80,000	5.97	0.022*
Hashimoto and Chen (1981)	400	13.71	0.319†
	4,000	5.46	0.075†
	40,000	2.77	0.025†

*Does not include electrical generation costs.
†Includes CO_2 removal to improve generator set efficiency.

TABLE 18. COMPARISON OF ESTIMATED PRODUCTION COSTS FOR MANURIAL BIOGAS AND BIOGAS GENERATED ELECTRICITY WITH COSTS FOR CONVENTIONAL ENERGY SOURCES.

Energy Source	Unit Cost*	Unit Cost, $/GJ
Fuel Oil, No. 2	$0.325/ℓ	$ 8.10
Liquified Petroleum Gas	0.198/ℓ	7.76
Natural Gas	0.155/m^3	4.05
Coal, Anthracite	0.109/KG	3.60
Electricity	0.05/KwH	13.89
Biogas		
Dairy Manure	--	$1.89 to 9.00†
Beef Cattle Manure	--	2.77 to 13.71††
Biogas Generated Electricity		
Dairy Manure	$0.036 to 0.32/kWh†	---
Beef Cattle Manure	0.022 to 0.319/kWh††	---

*Consumer prices excluding taxes, Ithaca, New York, January 1981.
†Range of values, Table 16.
††Range of values, Table 17.

Although the biogas production cost estimates summarized in Tables 16 and 17 appear to be reasonable, the differences among these estimates should be viewed critically. As shown in Tables 19 and 20, the assumptions underlying these estimates vary substantially. For example, the value for net energy production, GJ/cow-year, assumed by Jewell et al. (1980) is substantially higher than the values used by other investigators for biogas produced form dairy manure (Table 19) reflecting a lower estimate of biogas requirements for digester heating. The differences in interest rates used for amortizing capital costs also should be noted. Current (1981) interest rates are about 16 percent.

Biogas Utilization

It is generally agreed that effective utilization of essentially all available energy is critical to the economic feasibility of producing biogas from livestock and poultry manures. Manurial biogas can be used as a fuel for trucks, tractors, and other vehicles, as a boiler fuel, and as a fuel for on-site generation of electricity. The following discusses and analyzes these utilization options.

TABLE 19. COMPARISON OF ASSUMED VALUES USED IN ESTIMATING THE COST OF PRODUCING BIOGAS FROM DAIRY CATTLE MANURE.

Source	No. of Animals	Net Energy Output, GJ/YR	Net Energy Output, GJ/COW-YR	Capital Cost, $	Capital Cost, $/GJ net	Interest Rate, %	Labor Required, HR/YR
Abeles et al. (1978)*	100	590	5.9	$22,500	38.14	9.5	144
Coppinger et al. (1979)†	200	1108	5.5	55,100	49.74	12.0	219
	400	2216	5.5	84,700	38.22		328
Persson et al. (1979)†	100	760	7.6	20,000	38.14	6.0	548††
Jewell et al. (1980)*	50	456	9.1	15,400	33.75	10.0	102
	100	956	9.6	20,800	21.73		165
	500	4964	9.9	53,500	10.77		665

*Earth supported, plug flow digester.

†Conventional type, rigid wall digester.

††Not included in biogas production cost estimate.

TABLE 20. COMPARISON OF ASSUMED VALUES USED IN ESTIMATING THE COST OF PRODUCING BIOGAS FROM BEEF CATTLE MANURE.

Source	No. of Animals	Net Energy Output, GJ/YR	Net Energy Output, GJ/COW-YR	Capital Cost, $	Capital Cost, $/GJ net	Interest Rate, %	Labor Required, HR/YR
Hashimoto et al. (1978)*	10,000	46,100	4.6	901,000	19.54	9	†
Lizdas et al. (1980)††	80,000	121,276	1.5	3,085,000	25.44	9	12,000
Hashimoto et al. (1981)*	400	2,039	5.1	65,000	31.88	14	†
	4,000	20,929	5.2	327,000	15.62	14	†
	40,000	211,359	5.3	1,640,000	7.76	14	†

*Thermophilic digestion, 55°C.

†Labor included in cost estimates but requirements, HR/YR, not stated.

††Mesophilic digestion, 35°C.

The well documented dependence of production agriculture on gasoline and diesel fuel for the operation of trucks, tractors, and other vehicles has made using biogas conceptually attractive as a substitute. However, typical manurial biogas containing 60% methane has an energy density of 22.2 MJ/m^3 which is substantially less than that of liquid fuels including liquified petroleum gas (Table 21). Even with removal of carbon dioxide, the energy density of refined biogas (100% methane) is still slightly less than even that of natural gas due to the absence of heavier hydrocarbons such as ethane and propane.

TABLE 21. COMPARISON OF THE ENERGY DENSITIES OF BIOGAS AND METHANE TO NATURAL GAS AND LIQUID FUELS.

Fuel	Energy Density*
Biogas (60% Methane)	22.2 MJ/m^3†
Refined Biogas (100% methane)	37.0 MJ/m^3†
Natural Gas (79% CH_4, 14% C_2H_6)	38.3 MJ/m^3†
Gasoline	35,600 MJ/m^3 (35.6 MJ/ℓ)
Diesel Fuel, No. 2-D†† Fuel Oil, No. 2††	40,100 MJ/m^3 (40.1 MJ/ℓ)
Liquified Petroleum Gas	25,500 MJ/m^3 (25.5 MJ/ℓ)

*Schlesinger et al., 1978
†20°C, 760 mm
††ASTM grades

Although the energy density of refined biogas can be substantially increased by compression (Table 22), it still is not comparable to liquid fuels. Thus, sizable fuel tanks would permit only limited periods, one to two hours, of vehicle operation (Table 23). In addition the energy required for compression is not insignificant. Smith et al. (1977) estimates that 11.2% of the energy available in uncompressed methane would be required for compression to 3.4 MPa.

In order to achieve an energy density that is comparable to liquid fuels, liquification of refined biogas is necessary (Table 22). However, unlike propane and butane which are the principal constituents of liquified petroleum gas, methane is difficult to liquify due to its low critical temperature, -82.4°C (Katz et al, 1959). Above this temperature, methane cannot be liquified solely by pressure; refrigeration also is necessary. In contrast, both propane and butane can be liquified at ambient

TABLE 22. EFFECT OF COMPRESSION ON THE ENERGY DENSITY OF REFINED BIOGAS WITH COMPARISON TO LIQUID FUELS.

Fuel	Pressure, MPa* Gauge	Energy Density, MJ/m^3
Refined Biogas (100% methane)	0	37
	0.7	293
	1.4	550
	2.1	818
	2.8	1,099
	3.4	1,380
Liquified Methane	4.6	23,300
Gasoline	---	35,600
Diesel Fuel, No. 2-D	---	40,100
Liquified Petroleum Gas	2.0	25,500

*Pascals x 10^6; LB_f/in^2 x 6.89 x 10^6 = MPa

TABLE 23. QUANTITIES OF BIOGAS EQUIVALENT TO ONE LITER OF GASOLINE OR DIESEL FUEL.

	Pressure, MPa Gauge	Volumetric Equivalent to -	
		Gasoline, ℓ	Diesel Fuel, ℓ
Biogas (60% methane)	0	1603.6	1806.3
	0.7	199.2	224.4
	2.0	52.3	58.9
	7.0	76.3	86.0
Refined Biogas (100% methane)	0	962.2	1083.8
	3.4	25.8	29.0
	7.0	13.0	14.7

temperatures (Table 24). In addition to the need for refrigeration, almost all impurities must be removed before the methane component of biogas can be liquified. Typical requirements are no more than 0.002% carbon dioxide, 0.0001% water, and 2.3 x 10^{-5} mg of hydrogen sulfide per m^3 of gas (Kohl and Risenfield, 1974). Molecular sieves would probably be necessary to achieve this level of purification. Using the Linde process, approximately 30% of the energy available in uncompressed methane would be required for liquification (Smith and Van Ness, 1959).

TABLE 24. CRITICAL PROPERTIES OF METHANE, PROPANE, BUTANE AND CARBON DIOXIDE (KATZ ET AL., 1959).

Compound	Critical Temperature, °C*	Critical Pressure, MPa Gauge†
Methane (CH_4)	-82.4	4.6
Propane (C_3H_8)	93.5	4.3
Butane (C_4H_{10})	152.0	3.8
Carbon Dioxide (CO_2)	31.0	7.4

*That temperature above which a gas can not be liquified by pressure alone.
†That pressure under which a substance may exist as gas in equilibrium with a liquid.

Although use of biogas as a fuel for trucks, tractors, and other vehicles is technically feasible, this method of utilization is not generally viewed as practical particularly in situations where liquid fuels are available. Even with carbon dioxide removal and compression, the low energy density of methane would permit only limited periods, one to two hours, of vehicle operation even with sizable fuel tanks. In order to be competitive with liquid fuels, liquification of refined biogas which is technically complex and significantly reduces the quantity of available energy is necessary.

Of the available alternatives, use of biogas as a boiler fuel to produce heat, hot water, or steam is the most attractive from standpoints of simplicity and thermal efficiency. It also can be attractive economically if costly energy sources such as fuel oil, liquified petroleum gas, and electricity can be replaced. However, on-farm use of boiler fuels and therefore opportunities for using biogas as a substitute are limited as illustrated by Table 25. For large beef cattle feedlots, opportunities for using biogas as a boiler fuel also are limited. Sweeten (1979) estimated

TABLE 25. OPPORTUNITIES FOR ON-FARM USE OF BIOGAS AS A BOILER FUEL. (Jewell et al., 1976).

Fuel	40 Cow Dairy		100 Cow Dairy		1000 Head Beef Feedlot	
	Amount	GJ x 10^2/yr	Amount	GJ x 10^2/yr	Amount	GJ x 10^2/yr
Gasoline	5,530 ℓ	1.97	13,700 ℓ	4.88	26,685 ℓ	9.50
Diesel Fuel	2,760 ℓ	1.08	8,270 ℓ	3.32	26,190 ℓ	10.50
Electricity*	25,160 KwH	0.90	37,900 KwH	1.36	38,520 KwH	1.39
Boiler Fuels						
- Fuel Oil	6,435 ℓ	2.58	6,435 ℓ	2.58	13,170 ℓ	5.28
- Electricity†	11,800 KwH	0.42	24,350 KwH	0.88	18,000 KwH	0.65
Total		6.95		13.02		27.32
Biogas Production††		4.52		10.30		58.40
Boiler Fuels, % of Biogas Production		66.4%		33.6%		10.2%

*Excluding water and space heating

†For water and space heating

††Net energy production, plug flow digester

that only 30% of the biogas produced on a 30,000 head beef feedlot could be used on-site as a boiler fuel, primarily for steam flaking of corn or sorghum.

Sale of biogas as substitute natural gas (SNG) also is possible. However, biogas purification which involves removal of carbon dioxide, hydrogen sulfide and water vapor to levels specified for pipeline quality natural gas and compression are required prerequisites. Even for large feedlot size systems, biogas purification to meet pipeline quality standards is costly. Hashimoto et al. (1979) estimated that biogas purification equipment necessary for the sale of manurial biogas as SNG would account for 30% of the total cost of a biogas production system for a 10,000 head beef cattle feedlot. Thus, sale of biogas as SNG can not be realistically viewed as a possible option for smaller farm size systems.

Since the low energy density of biogas makes it generally unsuitable for use as a vehicular fuel and demand for boiler fuels on farms and feedlots is limited, on-site generation of electricity appears to be the most practical and generally applicable biogas utilization alternative. This utilization option is particularly attractive since the Public Utility Regulatory Policies Act of 1978 (PURPA) requires utilities to offer to purchase electrical energy and capacity from co-generation and small (less than 80 MW rated capacity) power producing facilities that use renewable resources such as biogas as a primary fuel (Berger et al., 1978). Thus, biogas utilization is not necessarily limited to on-site demand for electricity. The following examines the biogas utilization approach focusing on the factors that affect income realized and therefore economic feasibility.

The revenue that can be derived from biogas generated electricity is dependent on several inter-related variables. One is the cost of purchased electrical energy which determines the monetary value of biogas generated electricity used on-site. Unlike other forms of energy, the cost of purchased electrical energy and thus the value of biogas generated electricity used as a replacement varies substantially. In late 1981, the cost of electricity in the U.S. ranged from less than $0.05/KwH to over $0.10 KwH reflecting differences in methods of generation, fuels used, etc., among utilities. The cost of purchased electricity from an individual utility also can vary depending on quantity used, peak demand, and time of use.

Another variable affecting the revenue that can be realized is the price that is paid by utilities for purchased electrical energy. Although PURPA requires electric utilities to purchase biogas generated electricity, the price paid may be substantially less than the value of electricity utilized on-site. Under rules issued by the Federal Energy and Regulatory Commission, state public utility commissions are required to establish rates for electrical energy purchased from co-generation and small power producing facilities using "avoided cost" as the basis for rate making (Schiefen, 1981).

Avoided cost is the cost that a utility would incur if it were to generate or purchase from another source an equivalent amount of power. If the utility has adequate generating capacity, avoided cost is the cost of fuel not used. This may be less than $0.02/KwH for coal or exceed $0.06/KwH for oil generated electricity (New York State Electric and Gas Corporation, 1981). Avoided cost also may include costs that would be associated with construction of additional generating capacity or long term contractual purchases from other utilities. If the price paid for biogas generated electricity is based solely on the cost of fuel not used, there will be a substantial difference between the value of electricity used on-site and sold. Including avoided costs related to generating capacity would significantly reduce this differential, reflecting only distribution and administrative costs.

It is generally agreed that on-farm generation of electricity using biogas should be done in parallel with an electric utility to eliminate the need for generating capacity to meet peak demands and to facilitate sale of excess electrical energy. Maximizing on-site use of biogas generated electricity is most desirable, however, due to the previously discussed rate differential. The impact of this rate differential on income produced by biogas generated electricity for a 100 cow dairy farm is illustrated in Figure 13. In this example, reducing on-site utilization from 80% to 40% reduces income by $840/year.

The revenue derived from biogas generated electricity also is a function of the efficiency of this conversion process. As illustrated by Table 26, reported values for the thermal efficiency of converting biogas to electricity and therefore the fuel cost per KwH of electrical energy produced vary significantly. Thermal efficiency affects not only the quantity of electricity produced and the fuel cost/KwH but also generated cost. Koelsch and Walker (1981) have estimated a cost of $0.018/KwH for converting biogas to electricity at a thermal efficiency of 20%. At a thermal efficiency of 17.6% (Table 26), generation cost will increase to $0.020/KwH.

Waste heat recovery and utilization is commonly cited as a method of enhancing the thermal efficiency of the biogas to electricity conversion process. As shown in Table 27, approximately three-quarters of the energy input for an internal combustion engine is converted to heat. A reasonably well designed waste heat recovery system should capture about two-thirds of this thermal energy for digester heating and other uses. As shown in Tables 28 and 29, a substantial fraction of recovered waste heat can be utilized in northern climates. Demand, however, exceeds availability in winter months and there is a substantial surplus during the summer. Thus, the significance of waste heat recovery and utilization on the thermal efficiency of the biogas to electricity conversion process is dependent on climate and by extension geographical location.

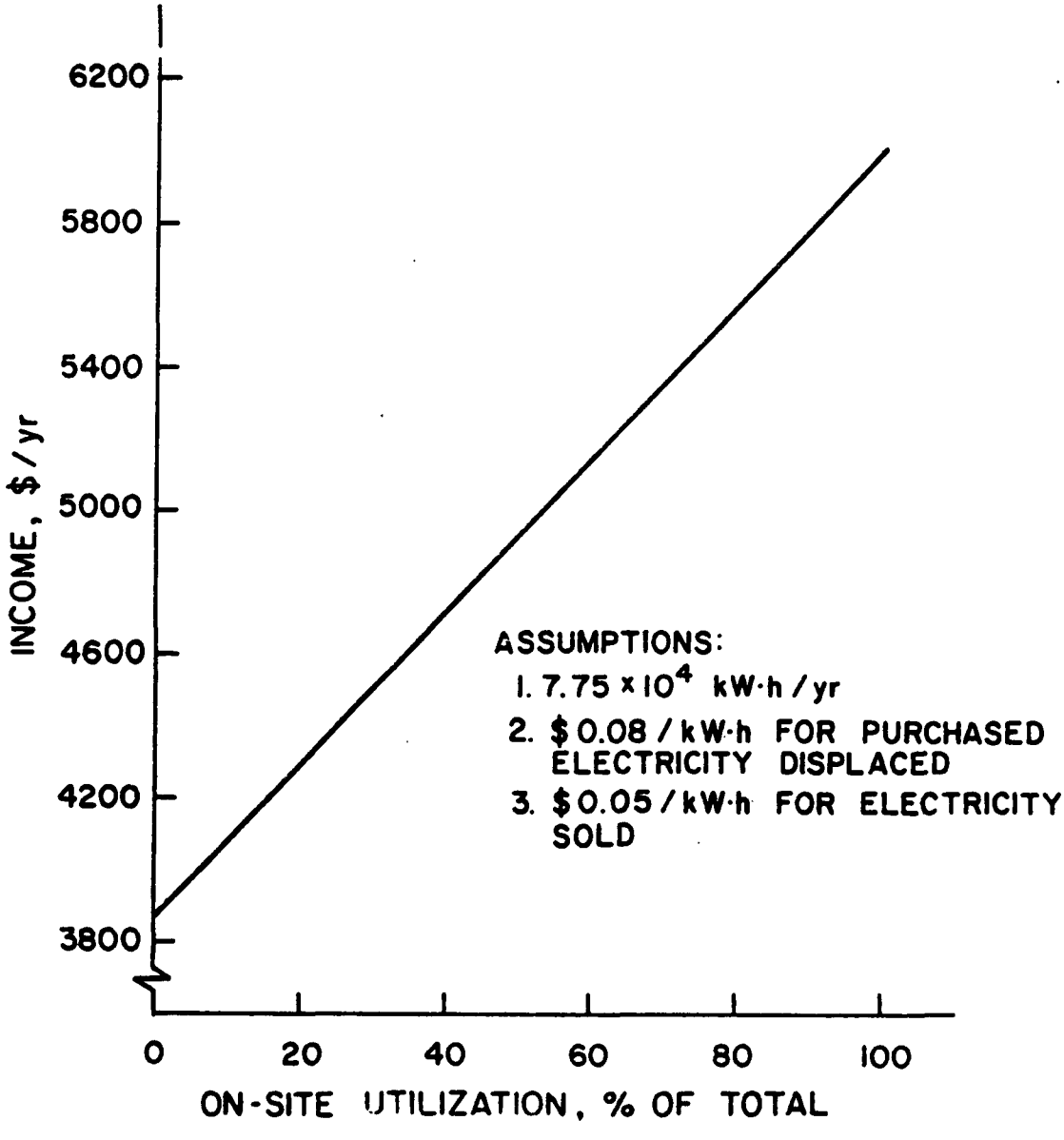

Figure 13. Relationship Between On-Farm Utilization of Biogas Generated Electricity and Resultant Income for a 100 Cow Dairy Farm.

TABLE 26. EFFECT OF THERMAL EFFICIENCY ON FUEL COST FOR BIOGAS GENERATED ELECTRICITY.

Engine Type	Fuel Consumption, MJ/HR		Fuel Cost, $/HR*	Thermal Efficiency, %†	Electrical Output, KW/HR	Fuel Cost/ kWh,$/kWh
	Biogas	Diesel Fuel				
Spark Ignited††	511	---	2.56	17.6	25	0.102
Spark Ignited#	351	---	1.76	20.6	20	0.088
Diesel#	329	60	2.13	18.6	20	0.106
Diesel§	289	48	1.83	30.0	28	0.065

*Biogas - $5.00/GJ, Diesel Fuel - $8.10/GJ.
†From biogas to electricity
††Coppinger et al., 1979
#Persson and Bartlett, 1981
§Ortiz-Canavate et al., 1981

TABLE 27. A TYPICAL HEAT BALANCE FOR A SPARK IGNITED L-HEAD ENGINE. (Obert, 1968).

	Heat of Combustion, %	Coolant Load, %
Engine Coolant		
Exhaust Port	7	18
Head	19	49
Cylinder	13	33
Subtotal	39	100
Exhaust Gases	37	
Friction	4	
Brake Power	18	
Unaccounted	2	
Total	100	

By-Product Recovery

Cost analyses by several investigators; Burford and Varani (1978), Hashimoto et al. (1978), and Lizdas et al. (1980); have indicated that for large scale facilities such as those using beef feedlot manure as a feedstock the monetary value of biogas produced will only partially offset total production costs (Table 30). These investigators have concluded, however, that producing biogas from manure can be economically feasible due to the value of digested manure or constituents thereof as feedstuffs (Table 31).

TABLE 28. COMPARISON OF DEMAND FOR THERMAL ENERGY AND AVAILABILITY OF WASTE HEAT RECOVERED* FROM A BIOGAS FUELED ENGINE-GENERATOR SET ON A TYPICAL NEW YORK STATE 100 COW DAIRY (Koelsch and Walker, 1981).

Month	Demand, GJ†	Available, GJ††	Utilized	
			Quantity, GJ	Percentage
January	24.9	11.9	11.9	100
February	22.5	9.2	9.2	100
March	28.2	14.0	14.0	100
April	28.7	18.1	18.1	100
May	21.1	29.8	21.1	71
June	15.0	32.9	15.0	46
July	13.4	33.0	13.4	41
August	13.7	34.0	13.7	40
September	17.4	29.8	17.4	58
October	24.9	25.0	24.9	100
November	32.3	19.8	19.8	100
December	31.3	17.1	17.1	100
		274.6	195.6	

Utilized/Available = 71.2%

*50% recovery of biogas energy
†Excluding digester heating
††After digester heating

TABLE 29. COMPARISON OF DEMAND FOR THERMAL ENERGY AND AVAILABILITY OF WASTE HEAT RECOVERED* FROM A BIOGAS FUELED ENGINE-GENERATOR SET ON A TYPICAL CENTRAL IOWA FARM. (Smith et al., 1977).

Month	Demand, GJ†	Available, GJ††	Utilized	
			Quantity, GJ	Percentage
January	47.2	26.8	26.8	100
February	36.5	24.3	24.3	100
March	37.2	23.6	23.6	100
April	16.2	17.0	16.2	95
May	10.1	38.9	10.1	26
June	6.0	52.2	6.0	11
July	2.7	63.5	2.7	4
August	2.7	67.3	2.7	4
September	7.3	39.1	7.3	19
October	61.9 (47.7)§	38.8	38.8	100
November	87.9 (51.6)§	26.6	26.6	100
December	43.9	20.0	20.0	100
		438.1	205.1	

Utilized/Available = 48.6%

*55% recovery of biogas energy
†Excluding digester heating
††After digester heating
§Thermal energy required for drying corn

TABLE 30. ESTIMATED COSTS AND REVENUES FOR PRODUCING BIOGAS FROM BEEF FEEDLOT MANURE.

	Burford and Varani (1978)	Hashimoto, et al. (1978)	Lizdas, et al. (1980)
System capacity, head of feeder cattle	50,000	10,000	80,000
Total production costs, $/year	2,229,000*	390,400*	724,350
Methane value, $/year	475,000†	76,500†	258,700§
By-product credit, $/year (value of residue as a feedstuff)	2,378,000#	414,000**	3,138,800 †† (413,900)§§

* includes centrifugation of effluent for feedstuff recovery.
† $1.66 per GJ.
§ $3.00 per GJ.
# $83.00 per tonne of dry matter.
** $100.00 per tonne of dry matter.
†† $86.18 per tonne of crude protein (cottonseed meal equivalent).
§§ $11.34 per tonne of crude protein (urea equivalent).

This conclusion is based on the assumption that anaerobically digested beef cattle manure can be used to replace soybean or cottonseed meal in finishing rations for feeder cattle. In these cost analyses, it was implied that beef cattle manure prior to digestion has no nutritive or monetary value as a feedstuff since no opportunity cost for using this manure as a feedstock for biogas production was included. The logic underlying this assumption is unclear particularly when published values for the nutrient composition (Bhattacharya and Taylor, 1975 and Ensminger and Olentine, 1978) and the estimated monetary value (Smith and Wheeler, 1979) of beef cattle manure as a feedstuff are considered. In the following discussion, information concerning the value of anaerobically digested manures as feedstuffs is analyzed to determine if the previously noted assumption and conclusion are valid.

Nutrient Transformations--

In the cost analysis cited, it was suggested that anaerobic digestion increases or "enhances" the value of beef cattle manure as a feedstuff. This hypothesis also has been suggested by Jewell et al. (1978) and Meckert (1978). When nutrient composition data for beef cattle manure before and after anaerobic digestion are compared on a dry matter basis (Table 31), it appears that enhancement has occurred. On this basis, the concentrations of

crude protein and amino acids have increased and those of digestible fiber, cellulose and hemicellulose, are essentially unchanged. Comparison on a weight volume basis shows, however, that the digestion process has not increased but rather only concentrated crude protein and amino acids and then only on a dry matter basis.

TABLE 31. COMPARISON OF THE NUTRIENT COMPOSITION OF BEEF CATTLE MANURE BEFORE AND AFTER ANAEROBIC DIGESTION* (Prior and Hasimoto, 1981).

Component	Influent	Effluent	Grams per Liter Influent	Grams per Liter Effluent	Percent change, gm/liter Basis
Dry Matter	7.22%	3.98%	72.2	39.8	-44.9
	-% of Dry Matter-				
Cellulose	10.5	10.6	7.6	4.2	-44.7
Hemicellulose	26.2	20.1	18.9	8.0	-55.7
Lignin	3.1	6.4	2.2	2.6	+18.2
Crude Protein	34.8	61.6	25.1	24.5	- 2.4
Amino Acids	14.3	23.5	10.3	9.4	- 8.7
Gross Energy	4661†	4655†	336.5§	185.3§	-44.9
Ash	9.8	17.1	7.1	6.8	- 4.2

* Average of 5 and 13 day HRT, 55°C.
† Kilocalories per gram of dry matter.
§ Megacalories per liter.

Loss of dry matter during anaerobic digestion results from the microbial transformation of carbonaceous materials to methane and carbon dioxide which is a universal characteristic of the process. Thus, any constituent will appear to increase on a dry matter basis if the loss of that constitutent is less than the dry matter loss.

Although it may be suggested that the concentration of crude protein and amino acids enhances the value of beef cattle manure as a feedstuff, the validity of this suggestion is questionable. First, the loss of digestible fiber is a loss of available energy. Significant losses of digestible fiber occur when dairy cattle manure is anaerobically digested (Table 32). Simple carbohydrates (sugars and starches) and lipids also are reduced during anaerobic digestion (Table 33). These losses are not unexpected, however, since simple carbohydrates and lipids are readily available microbial substrates that are utilized for biogas synthesis.

TABLE 32. COMPARISON OF THE NUTRIENT COMPOSITION OF DAIRY CATTLE MANURE BEFORE AND AFTER ANAEROBIC DIGESTION* (Jewell et al., 1978).

Component	Influent	Effluent	Grams per Liter Influent	Grams per Liter Effluent	Percent change, gm/liter Basis
Dry Matter	8.00%	5.34%	80.0	53.4	-33.2
	-% of Dry Matter-				
Cellulose	24.2	21.0	19.3	11.2	-42.0
Hemicellulose	18.3	13.1	14.6	7.0	-52.0
Lignin	8.2	11.9	6.5	6.0	- 8.3
Ash	11.4	16.2	9.1	8.8	- 3.3

* 12 day HRT, 35°C.

TABLE 33. COMPARISON OF THE NUTRIENT COMPOSITION OF SWINE MANURE BEFORE AND AFTER ANAEROBIC DIGESTION (Fischer et al., 1978).

Component	Grams per Liter Influent	Grams per Liter Effluent	Percent Loss
Hemicellulose	11.79	4.35	63
Cellulose	7.07	2.70	62
Lipids	8.45	2.78	67
Protein	11.62	6.35	49
Volatile Acids	4.44	0.52	88
Starch	0.67	0.03	96
Glucose (free)	0.22	0.02	91
Lignin	2.54	2.57	--

Second, the concentration of nutrients on a dry matter basis is of value only if these nutrients can be effectively recovered. Results of studies involving centrifugation as a liquid-solids separation process suggest that this is not possible (Hashimoto et al., 1978). Estimated maximum recoveries for total solids and organic nitrogen using a polyelectroyte to enhance dewatering were 50% and 60%, respectively. Actual recoveries have been significantly lower (Tables 34 and 35).

TABLE 34. PERCENTAGES OF ANAEROBICALLY DIGESTED BEEF CATTLE MANURE CONSTITUENTS RECOVERED IN CENTRIFUGE CAKE (Hashimoto et al., 1978).

Parameter	Digester Rentention Time, Days		
	20	12	6
Total Solids	31 ± 2*	34 ± 4	35 ± 3
Volatile Solids	33 ± 2	32 ± 4	34 ± 3
Fixed Solids	24 ± 5	39 ± 7	39 ± 8
Suspended Solids	45 ± 2	49 ± 4	51 ± 3
Total Nitrogen	12 ± 1	13 ± 4	20 ± 4
Organic Nitrogen	18 ± 4	20 ± 4	23 ± 3
Number of Observations	4	16	9

* Mean ± standard deviation.

TABLE 35. COMPARISON OF THE NITROGEN AND AMINO ACID CONTENT OF ANAEROBICALLY DIGESTED BEEF CATTLE MANURE EFFLUENT AND CENTRIFUGE CAKE (Hashimoto, et al., 1978).

Parameter	Percent of Dry Matter	
	Effluent	Centrifuge Cake
Total Nitrogen	5.05	2.96
Organic Nitrogen	4.27	2.36
Total Amino Acids	25.25	13.44
Essential Amino Acids*	10.84	5.75

* Phenylalanine, threonine, methionine, valine, leucine, isoleucine, lysine, histidine, arginine.

These comparisons of the nutrient compositions of beef cattle, dairy cattle, and swine manures before and after anaerobic digestion indicate that the possible value of these materials as feedstuffs is decreased substantially.

Digestibility Studies--

Interest in using anaerobically digested beef cattle manure (effluent) and effluent solids concentrated by centrifugation (wet cake and dry cake) as feedstuffs has resulted in several digestibility studies to determine results are summarized in Tables 36 and 37. The data illustrate that using digested manure or constituents thereof as components of rations fed to

sheep and beef cattle typically decreased digestibility of dry matter, organic matter, energy, nitrogen, and other constituents. These decreases indicate that the manures fed were not comparable nutritionally to the conventional feedstuffs replaced.

The decreases in nitrogen digestibility (Tables 36 and 37) are particularly interesting in light of the previously noted assumption regarding the use of digested beef cattle manure as a substitute for soybean or cottonseed meal. The studies cited in Tables 36 and 37 also have shown that using anaerobically digested beef cattle manure as a feedstuff can create palatability problems which significantly reduce dry matter intake.

Feeding Trials--

The potential value of anaerobically digested beef cattle manure as a feedstuff also has been examined in a number of feeding trials. Results from studies with heifers and steers are summarized in Table 38. In the first study (Burford and Varani, 1978), wet centrifuge cake, 30% dry matter, replaced cottonseed meal, straw, and limestone in a steam flaked milo-alfalfa hay based finishing ration. Prior et al. (1981) used digester effluent, approximately 4% dry matter, in place of soybean meal in a ground corn-brome grass hay based finishing ration. In both of these feeding trials, negative as well as positive control rations were used. In the negative control rations, soybean meal was replaced by ground corn. In the trial involving heifers, undigested beef cattle manure (influent) also was evaluated as a replacement for soybean meal.

In the Burford and Varani study (Table 38), the use of wet centrifuge cake as a substitute for cottonseed meal significantly reduced feed consumption and weight gains. Feed conversion efficiency, kg of feed consumed/kg of weight gain, also was adversely affected but to a much lesser degree. The reduced level of feed consumption for the experimental ration indicates palatability could have been a problem. The authors noted that the wet centrifuge cake had a "strong" chemical odor resulting from the use of a commercially available feed preservative, "Grazon", which was added to the centrifuge cake.

The use of digester effluent (Prior et al., 1981) in place of soybean meal in a finishing ration for steers also reduced weight gain and feed conversion efficiency (Table 38) even though feed consumption increased. The steers fed the negative control ration also outperformed the positive control group in this feeding trial. In the subsequent feeding trial involving heifers, average daily gain for animals fed digester effluent was comparable to the positive control group (Table 38). However, average daily gain for the heifers fed the influent also was comparable to the positive control. Feed consumption and feed conversion efficiency data for this feeding trial have not been published to date (1982).

Results of feeding trials involving the use of digested beef cattle manure (effluent) and centrifuge cake (wet cake) also have been presented by Lizdas et al. (1980). In this study, a protein supplement in a steam flaked corn, corn silage, and beet pulp finishing ration was partially replaced.

TABLE 36. INFLUENCE OF DRIED CENTRIFUGE CAKE AS A COMPONENT OF RATIONS FOR SHEEP AND STEERS ON DRY MATTER INTAKE AND APPARENT DIGESTIBILITY (Prior et al., 1981).

	Percent of Ration Dry Matter			
	5	10	15	20
Sheep*				
Dry Matter Intake, kg/day	1.027	0.970	0.886	0.947
Apparent Digestibility, %				
Dry Matter	72.5	71.6	72.2	68.0
Organic Matter	73.5	73.5	75.2	71.5
Energy	70.2	70.0	71.4	68.1
Nitrogen	58.5	55.1	56.8	51.4
Ash	59.5	46.3	40.0	28.4
Steers†				
Dry Matter Intake, kg/day	4.85	5.37	4.91	5.36
Apparent Digestibility, %				
Dry Matter	77.2	71.1	72.1	62.9
Organic Matter	78.5	72.7	73.7	65.4
Energy	75.4	70.1	70.8	63.8
Nitrogen	63.4	60.3	61.8	54.2
Ash	51.2	31.5	50.6	28.0
ADF§	54.9	27.2	48.6	43.1
NDF# (cell walls)	62.5	59.5	61.0	66.9
Cellulose	59.8	38.8	59.4	56.5
Cell Contents	83.7	75.8	79.0	59.2

* Replacing alfalfa hay.
† Replacing brome grass hay, corn, soybean meal and limestone.
§ Acid detergent fiber.
# Neutral detergent fiber.

TABLE 37. INFLUENCE OF WET CENTRIFUGE CAKE AND EFFLUENT ON DRY MATTER INTAKE AND DIGESTIBILITY OF RATIONS FED TO SHEEP AND STEERS.

Feedstuff	% of Ration Dry Matter	Apparent Digestibility, %					Dry Matter Intake, kg/day	Feedstuff Reduced or Replaced
		Dry Matter	Organic Matter	Ash	Energy	Nitrogen		
Wet Cake*	0	69.9	69.9	---	---	52.5	11.7	Cottonseed
(to steers)	30	67.1	67.1	---	---	52.6	9.2	Meal
Effluent†	0	81.4	82.8	66.2	81.3	72.6	0.78	Soybean
(to sheep)	6.5	75.4	77.1	39.8	74.4	58.8	0.84	Meal
Effluent†	0	76.1	---	---	---	61.5	5.29	Soybean
(to steers)	6.5	73.9	---	---	---	61.5	5.50	Meal
	Neg. 0§	77.6	---	---	---	70.5	5.04	

* Richter (1979).

† Prior et al. (1981).

§ Negative control.

TABLE 38. PERFORMANCE OF BEEF CATTLE FED ANAEROBICALLY DIGESTED MANURE A FINISHING RATION COMPONENT.

	Total Weight Gain, kg.	Average Daily Gain, kg/Day	Feed Consumption, kg/Day	Feed Conversion Efficiency, kg/kg	Number of Animals	Duration of Study, Days
Burford and Varani (1978)						
Steers - Control	128.6	1.67	14.22	8.50	36	77
Wet Cake, 18%*	103.9	1.35	11.92	8.85	36	77
Prior et al. (1981)						
Steers - Control	159.0	0.93	8.21	8.83	10	168
Effluent, 6.45%†	136.9	0.80	8.55	10.69	10	168
Negative Control	162.2	0.94	7.59	8.07	10	168
Heifers - Control	108.0	1.28	§	§	20	126
Influent, 6.45%†	107.8	1.28	§	§	20	126
Effluent, 6.45%†	106.4	1.27	§	§	20	126
Negative Control	103.1	1.20	§	§	20	126

* % of ration, "as fed" basis.

† % of ration, dry matter basis.

§ Not reported.

Although reported values for average daily gain and feed conversion efficiency for both trials (Table 39) appear reasonable, neither positive nor negative controls were included in the experimental design for these feeding trials.

Results of future feeding trials may show that using anaerobically digested manures as feedstuffs significantly reduces unit feed costs, $ per kg of weight gain. It should be recognized, however, that unit fixed costs will increase if either average daily gain or feed conversion efficiency is adversely affected. This point has been commonly overlooked in studies evaluating the use of animal manures as feedstuffs.

ENVIRONMENTAL QUALITY IMPACTS

The production of biogas from livestock and poultry manures as well as the utilization of biogas as a fuel are generally viewed as attractive from an environmental quality standpoint. Both odor control and reduction of the water pollution potential of animal manures are commonly cited as important benefits. It has been suggested that anaerobic digestion could be designated as a best management practice (BMP) for addressing manure related nonpoint source water quality problems under provisions of the Clean Water Act (PL 95-217) addressing such problems (Office of Technology Assessment, 1980). Although such environmental quality benefits may result from anaerobic digestion, analysis of the significance of these possible benefits as well as impacts has been lacking. The objective of this section is to examine and discuss this subject.

Pollution Characteristics of Manures

Waste stabilization is frequently cited as an important benefit of using anaerobic digestion to produce biogas from animal manures. When concentrations of total and volatile solids and chemical oxygen demand in manure slurries before and after anaerobic digestion are compared (Table 41), it can be seen that substantial reductions do occur. These reductions, which are the result of the microbial conversion of carbonaceous compounds into methane and carbon dioxide, translate directly into reduced carbonaceous oxygen demand if these wastes enter surface waters.

It should be recognized, however, that the carbonaceous fractions of livestock and poultry manures are not completely stabilized during anaerobic digestion particularly at the short retention times, 10 to 15 days, necessary to economically optimize biogas production (Figure 14). In order to produce a highly stabilized effluent, a retention time of at least 30 days is necessary.

Although anaerobic digestion is a waste stabilization process, stabilization is limited to carbonaceous materials. As shown in Table 41, concentrations of manurial nitrogen and phosphorus are essentially unchanged by the digestion process. However, the fraction of manurial nitrogen present as ammonia and therefore the potential nitrogenous oxygen demand of manures is substantially increased. This oxygen demanding process, known as nitrification, is common in both terrestrial and aquatic environments.

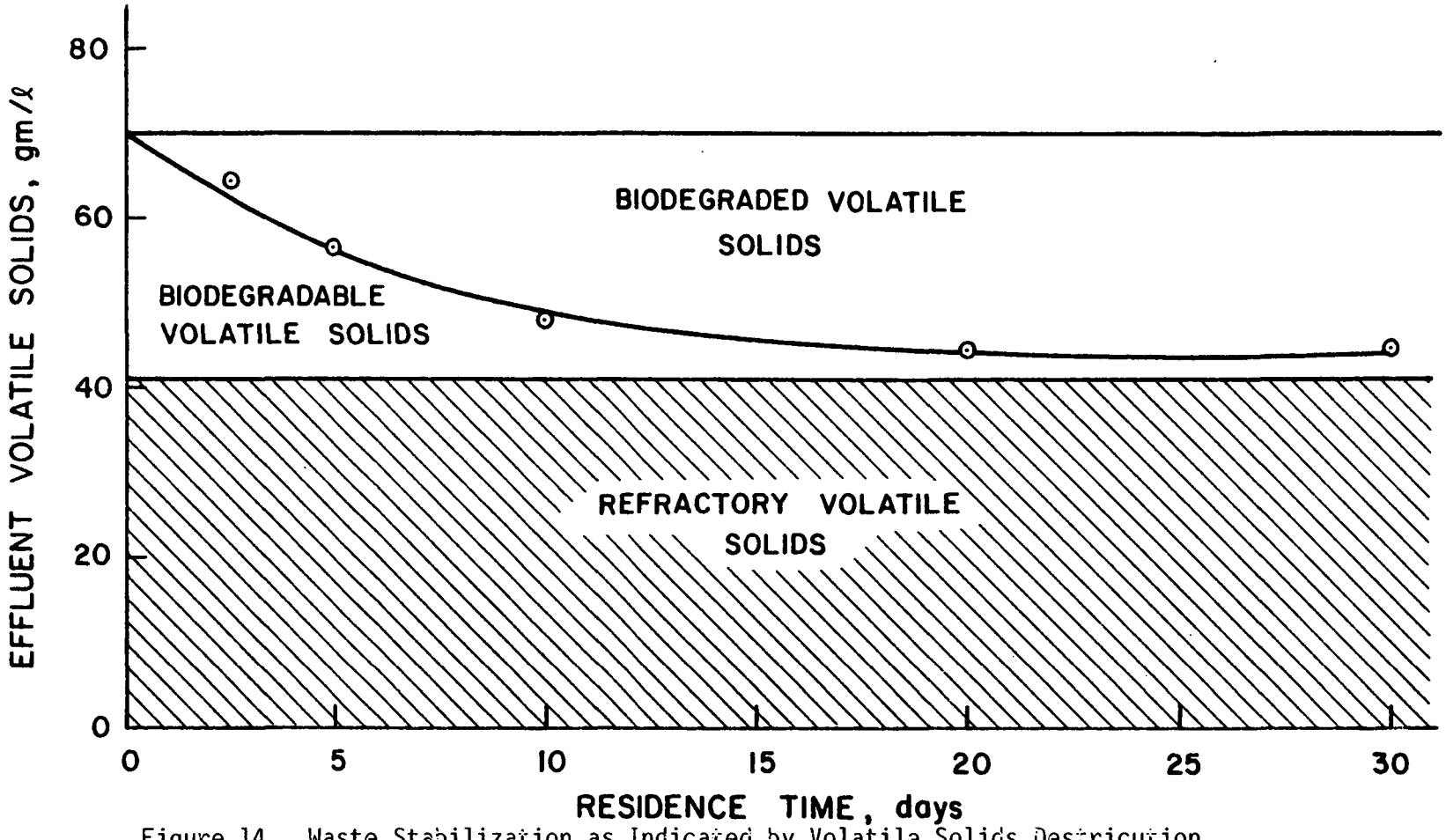

Figure 14. Waste Stabilization as Indicated by Volatile Solids Destruction as a Function of Digester Retention Time (Morris, 1976).

TABLE 39. PERFORMANCE OF BEEF FEEDER CATTLE FED ANAEROBICALLY DIGESTED MANURE AS A FINISHING COMPONENT (Lizdas et al., 1980).

	Total Weight Gain, kg	Average Daily Gain, kg/day	Feed Consumption, kg/day	Feed Conversion Efficiency, kg/kg	Number of Animals	Duration of Study, Days
Effluent*	115.5	1.7	10.5	6.3	20	69
Wet Cake*	90.6	1.5	10.4	6.9	19.5†	79

* Average crude protein content of 77 gm/head/day.

† Weighted average, 2 animals removed during the trial.

TABLE 40. COMPARISON OF THE PHYSICAL AND CHEMICAL CHARACTERISTICS OF LIVESTOCK AND POULTRY MANURES BEFORE AND AFTER ANAEROBIC DIGESTION.

Parameter	Laying Hen Manure*			Beef Cattle Manure†		
	Concentration, gm/liter		Change in Concentration, %	Concentration, gm/liter		Change in Concentration, %
	Influent	Effluent		Influent	Effluent	
Total Solids	113.7	56.0	-51	70.1	36.6	-48
Volatile Solids	76.5	32.1	-58	61.8	29.2	-53
Chemical Oxygen Demand (COD)	119.0	70.4	-41	74.9	40.2	-46
Total Nitrogen	8.8	9.2	+ 4	4.3	3.9	- 9
Ammonia Nitrogen as N	5.2	7.1	+36	1.1	1.9	+73
Phosphorus as P	2.9	2.1	-28	---	---	---
Potassium as K	3.4	3.6	+ 6	---	---	---

* Converse et al., 1981, 35°C, retention time 36-46 days.

† Hashimoto et al., 1978, 55°C, retention time 12 days.

Continued ...

TABLE 40. continued

Parameter	Dairy Cattle Manure††			Swine Manure§		
	Concentration, gm/liter		Change in Concentration, %	Concentration, gm/liter		Change in Concentration, %
	Influent	Effluent		Influent	Effluent	
Total Solids	77.5	59.0	-24	73.5	35.7	-51
Volatile Solids	64.9	45.8	-29	60.3	23.9	-60
Chemical Oxygen Demand (COD)	77.2	51.0	-34	80.6	35.9	-55
Total Nitrogen	2.6	2.9	+12	3.9#	4.1#	+ 5
Ammonia Nitrogen as N	0.9	1.3	+44	1.7	2.9	+70
Phosphorus as P	0.6	0.5	-17	1.3	1.2	- 8
Potassium as K	1.9	2.0	+ 5	1.2	1.2	0

††Converse et al., 1977, 35°C, retention time 10.4 days.
§ Fischer et al., 1978, 35°C.
# Total Kjeldahl nitrogen.

Stoichiometrically, 4.57 gm of oxygen are required for the oxidation of one gm of ammonia nitrogen to nitrate nitrogen. Thus, the nitrogenous oxygen demand exerted if anaerobically digested manures are permitted to enter surface waters will be substantial and probably differ little from undigested manures. Other water quality problems such as eutrophication resulting from soluble forms of phosphorus and ammonia toxicity to fish and other aquatic organisms also will be undiminshed.

Although the water quality benefits associated with manurial biogas production are questionable, it is clear that this process can provide a measure of odor control. Under controlled anaerobic conditions, the production of reduced compounds (organic acids, amines, mercaptans, and sulfides) which occur under uncontrolled anaerobic conditions and resultant odors are minimized. It is important, however, to recognize that although manure odors may be considerably reduced in both presence and offensiveness as noted by Welsh et al. (1977), they are not eliminated.

The actual environmental quality benefits of waste stabilization as a by-product of manurial biogas production depends on digester performance and total system management. Possible environmental quality problems will relate to odors and water quality impacts associated with storage and pasture and cropland disposal of digester effluent. The problems that do occur and the benefits realized will be the result, however, of management and not biogas production.

Biogas Utilization

The possible impacts of biogas utilization on air quality have received little attention. Data that are available indicate, however, that impacts should be minimal particularly with respect to emissions of oxides of sulfur (SO_x) and nitrogen (NO_x). The sulfur content of fuels determines the quantities of sulfur dioxide and sulfur trioxide produced during combustion. Formation of sulfur trioxide is negligible, however, with small scale combustion equipment where firebox temperatures do not exceed 420°C (Danielson, 1973). Nitric oxide and nitrogen dioxide emissions also are characteristic of combustion processes. These emissions appear to be primarily a function of temperature and equipment design (Danielson, 1973), but the presence of ammonia in fuels may increase emissions of nitrogen oxides (Kuo and Jones, 1978).

Although manurial biogas contains hydrogen sulfide, it compares favorably on the basis of sulfur content per unit energy with other fuels particularly coal and fuel oil derived from high sulfur crudes (Table 41). The difference in sulfur content between biogases produced from dairy and poultry manure should be noted. On the basis of combustion products produced, manurial biogas appears to compare favorably with conventional alternatives when used as a boiler fuel with conventional alternatives (Table 42).

Published information concerning emissions of air pollutants that occur when biogas is used to fuel internal combustion engines appears to be lacking. Reported values for methane indicate, however, that using biogas

to fuel internal combustion engines will increase emissions of oxides of nitrogen, carbon monoxide, and hydrocarbons when using biogas as a boiler fuel is the basis of comparison (Table 43). These higher emission levels are characteristic of internal combustion engines. Emission of sulfur oxides should be comparable.

TABLE 41. COMPARISON OF THE SULFUR CONTENT OF MANURIAL BIOGASES AND CONVENTIONAL FUELS.

Fuel	Sulfur, %, as S by wt.*	Sulfur, mg S/KJ
Anthracite Coal	0.8	0.27
High Volatile B Bitumenous Coal	2.8	1.03
Fuel Oil, Mid-continent	0.35	0.08
Fuel Oil, California	1.16	0.26
Diesel Fuel, No. 2-D	0.5 max.	0.11
Pipeline Natural Gas	trace	trace
Biogas 60% CH_4/40% CO_2		
Dairy Manure†	0.06-0.19	0.04-0.10
Poultry Manure§	0.16-0.71	0.09-0.39

* Schlesinger et al., 1978.
† Coverse et al., 1977.
§ Converse et al., 1981.

TABLE 42. COMPARISON OF SO_x AND NO_x EMISSIONS WHEN BIOGAS, NATURAL GAS, AND FUEL OIL ARE USED AS BOILER FUELS.

	gm/GJ	
	Sulfur Oxides (SO_x)	Nitrogen Oxides (NO_x)
Manurial Biogas		
Beef Manure*	310 (SO_2)	462
Poultry Manure*	387 (SO_2)	805
Natural Gas†	Insignificant	27 - 163
Fuel Oil, No. 6†§	720	236

* Kuo and Jones, 1978.
† Danielson, 1973.
§ No. 6 Fuel Oil, 1.6% sulfur by weight.

TABLE 43. COMPARISON OF AIR POLLUTANTS EMITTED WHEN METHANE IS USED AS A BOILER FUEL VERSUS AS A FUEL FOR INTERNAL COMBUSTION ENGINES (Brooklyn Union Gas Company, 1978).

	gm/m^3		gm/GJ	
Products of Combustion	Boiler Fuel	Internal Combustion Engine	Boiler Fuel	Internal Combustion Engine
Nitrogen oxides (NO_x)	8	72	227	2040
Carbon monoxide (CO_2)	3	8	91	230
Hydrocarbons	2	8	45	230

Estimates of the quantities of sulfur dioxide and nitrogen oxides generated in association with biogas production and purification are summarized in Table 44. Data for coal gasification are provided as a basis for comparison. These data indicate that air quality impacts of biogas production, with the possible exception of sulfur dioxide emissions related to biogas purification, should be of little concern. However, the

monoethanolamine gas purification process for removal of carbon dioxide and hydrogen sulfide is practical only for large scale systems. Thus, it appears that iron sponges will be more extensively utilized for removal of hydrogen sulfide. This is more desirable from the standpoint of air quality since elemental sulfur is the end-product of iron sponge regeneration.

TABLE 44. COMPARISON OF SO_2 AND NO_x EMISSIONS ASSOCIATED WITH MANURIAL BIOGAS PRODUCTION AND PURIFICATION WITH SNG PRODUCTION FROM COAL.

	Gm/GJ Net Energy	
	Sulfur Dioxide	Nitrogen Oxides
Biogas Production*		
Beef Manure, Fresh	46	69
Beef Manure, Feedlot†	97	80
Poultry Manure	387	805
Biogas Production and Purification§		
Beef Manure, Feedlot	2200#	78
SNG From Coal	43	Nil

* Kuo and Jones (1978).
† Manure accumulated over periods of 5-6 months.
§ Ballay et al. (1980) monoethanolamine process for purification.
\# Would be nil if iron sponge is used for H_2S removal.

SUMMARY

This section evaluated the feasibility of producing biogas from livestock and poultry manures using anaylses of technical, economic, and environmental quality considerations as a basis. As discussed, the technical feasibility of manurial biogas production has been demonstrated in a number of studies and a rational basis for system design and operation has been established.

The economic feasibility of manurial biogas production is less clear due to uncertainties concerning biogas production costs and biogas utilization. Of the available alternatives for biogas utilization, on-site generation of electricity appears to be the most practical and generally applicable. On-site generation of electricity in parallel with an electric utility permits utilization of all available biogas. However, revenues produced to offset production costs and provide the attractive rate of return to invested capital necessary to stimulate investments in this technology depend on several variables. These include the on-site demand for and the cost of electricity, the price to be paid by utilities for excess electrical energy, and opportunities for engine-generator set waste heat utilization.

An additional variable is the thermal efficiency of converting biogas to electricity which appears to be equipment dependent. Due to the site specific nature of these variables, the economic feasibility of this technology also should be viewed as site specific.

None of the available experimental evidence supports the assumption that anaerobic digestion "enhances" the value of animal manures as feedstuffs. Thus, the assumption of by-product credits made in several evaluations (Table 31) do not appear justified. Although anaerobically digested manures may have some value as feedstuffs, this value is, at best, only comparable to these manures "as produced". Thus, any by-product value realized would be offset by the opportunity cost associated with first using the manure as a feedstock for biogas production instead of directly as a feedstuff.

It does not appear that there are any readily identifiable negative environmental quality imputs of importance related to producing or utilizing manurial biogas. However, it also does not appear that there are any substantial environmental quality benefits associated with biogas production and utilization. One exception is odor control which appears to be the most attractive environmental quality aspect of manurial biogas production.

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