A Technology Assessment of Solar Energy Systems

Environmental Residuals and Capital Cost of Energy Recovery From Municipal Sludge and Feedlot Manure

MASTER

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FORWARD

The U. S. Department of Energy, Office of Environment, Office of Environmental Assessments, is conducting a project entitled Technology Assessment of Solar Energy (TASE) Systems, to evaluate the range of potential environmental, health, and socioeconomic consequences of rapid, large-scale commercialization of solar technologies. The goal of this project is to identify and analyze both the positive and negative effects of solar technology deployment. The project will provide a basis for avoiding potential problems and for grasping opportunities during the transition to solar energy in the U. S.

Massive solar development will force major increases in the use of those raw materials needed to make solar system components. Along with this increased resource consumption and production will come associated pollution. In addition, rapid solar energy development may mean significant secondary or unplanned changes in institutions and lifestyles as the nation moves toward greater use of solar energy systems. The TASE project is designed to provide a quantitative analysis of the direct and indirect effects of solar energy use. In so doing, it will help define an environmentally acceptable solar future.

This report is an element of the TASE Solar Technology Characterization Series. We would like to express our appreciation to Terry Surles of the Argonne National Laboratory for his efforts in preparing this document.

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ENVIRONMENTAL RESIDUALS AND CAPITAL COSTS OF ENERGY RECOVERY FROM MUNICIPAL SLUDGE AND FEEDLOT MANURE

by

Stephen W. Ballou, Larry Dale, Ron Johnson,
William Chambers, and Hank Mittelhauser

ABSTRACT

This report analyzes the capital and environmental cost of energy recovery from municipal sludge and feedlot manure. Literature on waste processing and energy conversion and interviews with manufacturers were used for baseline data for construction of theoretical models using three energy conversion processes: anaerobic digestion, incineration, and pyrolysis. Process characteristics, environmental impact data, and capital costs are presented in detail for each conversion system. The energy recovery systems described would probably be sited near large sources of sludge and manure, i.e., metropolitan sewage treatment plants and large feedlots in cattle-raising states. Although the systems would provide benefits in terms of waste disposal as well as energy production, they would also involve additional pollution of air and water. Analysis of potential siting patterns and pollution conflicts is needed before energy recovery systems using municipal sludge can be considered as feasible energy sources.

1 INTRODUCTION

During the past several years, a great amount of interest has been directed toward development and eventual utilization of solar energy technologies. In addition to using a seemingly inexhaustible energy source, solar technologies are generally perceived to be relatively benign in terms of environmental, health, and safety impacts. The amount of environmental impact, however, varies with the conversion technologies, especially when construction, material supply, and environmental costs are included.

Although solar technologies are generally considered to be those that use direct solar energy (as in photovoltaics) or energy sources that are once removed from direct sunlight (such as wind or ocean thermal gradients), they also include technologies that utilize biological wastes, such as crop residues, livestock manures, and municipal sludge. The purpose of this

study is to address the capital and environmental costs associated with energy recovery from municipal sludge and feedlot manures. Several conversion systems are evaluated to determine material requirements, capital costs, and environmental costs, the latter in terms of land and water requirements and production of effluent and residual pollutants. Results of this study will be used by the Department of Energy to evaluate impacts resulting from the future deployment of solar technologies. To that purpose, some of the findings of this study (e.g., energy production) are expressed in terms of Quads (10^{15} Btu) as required for incorporation into the Strategic Environmental Assessment System (SEAS), a computer program that is used to evaluate the impacts of energy-related policies on the U.S. economy and environment.

1.1 METHODOLOGY

Our approach to the study began with collection of the necessary base data on process designs and operating parameters. The literature is not voluminous and does not contain all of the base information that we required; therefore we interviewed, over the telephone, many manufacturers and users of waste-processing and energy-conversion equipment to verify or update design parameters and operating costs. In some cases neither the literature nor our telephone informants could give us firm figures. In these cases it was necessary to assume plant designs and operating parameters on the basis of characteristics of similar equipment commonly used in other industrial processes. From these basic engineering assumptions, it was then possible to calculate the required cost and environmental details.

Several assumptions were made in evaluating pollution and cost data for the conversion systems described in this report. In the case of sludge conversion systems, we assumed that conversion facilities would be located on the same sites as existing wastewater treatment plants. Capital costs, therefore, would relate only to the additional conversion facilities. Consequently, collection and transportation costs are not assumed, since they are already included in the normal operation of treatment plants. Likewise, for feedlot manure conversion, we assumed that collection and transportation costs are already borne by the feedlot operators, who collect, transport, and sell large quantities of manure for fertilizer as part of their normal operation.¹

The description of municipal sludge conversion systems is based on the assumption that energy recovery from sludge will occur in relatively large metropolitan areas. High capital costs and large energy requirements will demand large quantities of sludge. For the manure conversion technologies, large quantities of manure will be required. Scaling down pyrolysis systems is difficult because of the high capital costs. Anaerobic digestion of manure, however, can be scaled down to smaller, decentralized operations.

1.2 FEEDSTOCK CHARACTERISTICS

1.2.1 Municipal Sludge

Municipal sludge is a combination of human excrement, garbage grindings, industrial plant discharges, silt and grit from storm runoff, and biologically produced solids, all mixed in highly variable proportions. Sludge solids are normally defined in terms of total solids and volatile solids. The volatile solids are the organic fraction of solids, from which energy may be recovered. Volatile solids range from 60% to 80% of total solids;² we have assumed approximately 75% of the total solids. Thus, assuming an energy content of 10,000 Btu per pound of volatile solids, the heating value of sludge is 7,500 Btu/lb.

The chemical composition of the volatile solids is also highly variable; we have assumed the composition shown in Table 1.1. The heavy-metal content of sludge solids is assumed to be as shown in Table 1.2.

1.2.2 Manure

Cattle manure generally consists of spilled and undigested feed, lignin and hemicellulose material from undigested roughage, and ligno-protein complexes produced within the animal. Manure production rates from feedlot cattle average 60 wet pounds per head per day, or 6.9 pounds of dry solids per head per day, of which 86% is organic and therefore convertible to energy. Waste production by other livestock is shown in Table 1.3.^{3,4} Table 1.4 shows the typical composition of semicomposted manure in a nonarid climate.⁵ In general, the heating value of dry, ash-free manure is 8,750 Btu/lb.

Table 1.1. Assumed Composition of Municipal Sludge Solids

Component	Percent by Weight
Carbon	37.6
Hydrogen	5.2
Oxygen	27.0
Nitrogen	4.5
Sulfur	0.7
Nonvolatile Solids	25.0
Total	100.0
Heating value (Btu/lb) ^a	7,500

^aAssuming 10,000 Btu/lb for volatile solids.

Table 1.2. Metal Content of Municipal Sludge

Metal	In Dry Solids		lbs/100 lbs Volatile Solids
	ppm	lbs/ton	
Arsenic	43	0.086	0.0057
Beryllium	- a	- a	- a
Cadmium	25	0.05	0.0033
Chromium	1,000	2.0	0.133
Copper	1,000	2.0	0.133
Lead	1,000	2.0	0.133
Mercury	10	0.02	0.00133
Nickel	200	0.4	0.0265
Selenium	26	0.05	0.0034
Silver	225	0.45	0.03
Zinc	2,500	5.0	0.331

^aNot detected.

Source: Ref. 2.

Table 1.3. Summary of Animal Waste Characteristics^a

Waste Component	Dairy Cow	Beef Feeder	Swine Feeder	Sheep Feeder	Horse	Poultry	
						Layer	Broiler
Raw Manure ^b	82	60	65	40	45	53	71
Total Solids	10.4	6.9	6.0	10.0	9.4	13.4	17.1
Volatile Solids	8.6	5.9	4.8	8.5	7.5	9.4	12.0
Biochemical Oxygen Demand	1.7	1.6	2.0	0.9	-	3.5	-
Chemical Oxygen Demand	9.1	6.6	5.7	11.8	-	12.0	-
Nitrogen (total, as N)	0.41	0.34	0.45	0.45	0.27	0.72	1.16
Phosphorous (as P)	0.073	0.11	0.15	0.066	0.046	0.28	0.26
Potassium (as K)	0.27	0.24	0.30	0.32	0.17	0.31	0.36

^aPounds of component per day per 1000 live pounds of animal.

^bFeces and urine with no litter or bedding.

Source: Refs. 3,4.

1.3 APPLICATIONS SELECTED FOR STUDY

Three processes for energy recovery from municipal sludges and manures were evaluated in this study: anaerobic digestion, incineration, and pyrolysis. The rationale for selection of these processes is discussed below. In general, these technologies have a long history of application in the United States, and their operating behaviors are well understood. They will likely continue to be the primary technologies for sludge and manure conversion through 1990.

1.3.1 Anaerobic Digestion

Municipal Sludge. Anaerobic digestion of municipal sludge can be used to recover energy from sludge while simultaneously destroying pathogenic organisms and odors associated with the sludge. Interest in this process has recently revived because of the benefits of methane production, improved operability due to increased understanding of the technology, and the effect of producing a more readily disposable sludge.⁶ The digested sludge is usable as a soil conditioner, but its application to cropland can be limited by its nitrate and heavy-metals content. However, recent changes in water pollution control statutes, requiring industrial plants to clean their water discharges, may increase the usefulness of digested sludge as a soil conditioner. Coupling the energy production of anaerobic digestion with the

Table 1.4. Composition of Semicomposted Manure

Component	Weight %, Weight %	
	Wet	Dry, ash-free
Carbon	18.9	52.2
Hydrogen	2.3	6.4
Oxygen	13.3	36.9
Nitrogen	1.2	3.3
Sulfur	0.4	1.2
Ash	13.9	-
Water	50.0	-
Total	100.0	100.0
Heating Value (Btu/lb) ^a	-	8,750

^aCalculated from Dulong's formula.

prospect of using municipal sludge as a soil conditioner changes the treatment of municipal sludge from a waste disposal problem to a resource recovery opportunity.

The energy product resulting from anaerobic digestion of municipal sludge is a methane-carbon dioxide mixture that can be used in any power-generating equipment that burns a gaseous fuel. Carbon dioxide content ranges from 15% to 50% by volume; removal of the carbon dioxide and other impurities leaves methane gas suitable for pipeline feed. Unfortunately, the amount of gas producible in this way from municipal sludge is negligible in comparison to the volumes of natural gas used by municipalities. Nevertheless, digester gas could provide a large part of the power needed (and at present, purchased) by municipalities for wastewater treatment. In this work we have assumed that digester gas would be used as fuel at the wastewater treatment plant that would produce the sludge fed to the digester. Other uses are possible, but we have not analyzed them in this study.

Manure. Anaerobic digestion of animal residues has been used in India for many years. Sanghi and Day⁷ report that in 1972 there were about 2,500 digesters in rural India producing biogas from cattle dung without destroying the value of the solids as fertilizer. Essentially, only carbon is driven off in the digestion process, yielding gas with a heating value of 600 Btu/ft³. The nutrients in fresh dung pass through and are discharged in the digested residue, which loses only a small part of the nitrogen.³ Digested manure is considered a good source of animal feed, in addition to its utility as fertilizer.

In the United States, extensive investigations are under way to evaluate process requirements for biogas recovery from manure from feed cattle, dairy cows, swine, and poultry and from other animal wastes.⁸⁻¹⁰ One area where anaerobic digestion is close to full-scale production is the Four Corners region of Arizona, Colorado, New Mexico, and Utah, where there are many large beef feedlots.

The process characteristics reported here are based on a model plant (described in a later section) designed to process the waste from 25,000 beef cattle.

1.3.2 Incineration

Recovery of energy by sludge incineration involves raising steam by cooling the hot flue gases. The steam may be used for heating, but the most attractive possibility is to use steam turbines to drive motors directly, or produce electricity for the same use, in an associated wastewater treatment plant.

Incineration is primarily a means of reducing the weight and volume of municipal sludge prior to final disposal. Use of this technology is increasing because of its sludge reduction capability as well as the opportunity it presents for recovering energy from the sludge.

The two sludge incineration techniques most common in the United States differ in the type of furnace employed. Multiple-hearth furnaces are most widely used, but fluidized bed incinerators are also used in a significant number of the installations where incineration is practiced.

The multiple-hearth furnace is shaped like a vertical cylinder and consists of an insulated steel shell surrounding a number of solid refractory hearths, one above the other, and a central rotating shaft to which rabble arms are attached. The hearths are constructed of high-heat-duty fire brick. Air and combustion gases flow up through the furnace, and sludge moves downward. Gas, oil, coal, or solid municipal waste may be used as auxiliary fuel for start-up or supplemental fuel in the incinerator. The sludge is dried in the upper hearths, where the sludge temperature is raised to about 200°F and most of the moisture is driven off. The gas temperature in this zone may be as low as 800°F or as high as 1,400°F. The sludge burns in the middle hearths, where the temperature is about 2,000°F. The bottom hearths compose the ash cooling zone, in which the incoming air cools the ash to around 400°F before the ash leaves the furnace. The multiple-hearth furnace typically operates with 75-100% excess air. The excess of air insures that proper turbulence and mixing occurs, that the sludge is completely burned, and that the combustion gases are cool enough to protect the refractory lining of the hearth. The central shaft and rabble arms are cooled by air flowing through tubes in their cores.

Fluidized-bed incinerators are vertical cylindrical vessels with a grid near the bottom to support a sand bed. Dewatered sludge is injected above the grid, and air (at 20-25% excess) is injected below the grid at 3 to 5 psig; the air flows upward, fluidizing the hot sand-and-sludge mixture. Supplemental fuel may be introduced above or below the bed. The single chamber is operated at about 1,500°F, and drying and combustion occur simultaneously in the bed.

1.3.3 Pyrolysis

Pyrolysis in the absence of oxygen reduces biomass to produce useful fuels and chemicals. Hydrocarbons are thermally decomposed into a hydrogen-enriched volatile phase and a carbonaceous char. At low pyrolysis temperatures, the volatile phase is composed of heavy, unsaturated hydrocarbons that are liquid, possibly even solid, at room temperature. Higher operating temperatures cause further cracking of the volatile hydrocarbons so that light hydrocarbon gases are the principal products.

Volatile products of pyrolysis can be used as chemical feedstocks and as fuels. Economics will determine which application is best for these materials. For instance, the relatively low energy content of pyrolysis gases from manure may preclude transportation over any substantial distances. This means the potential markets for pyrolysis products must be nearby, or additional processing will be required to upgrade these products to materials of higher value.

Pyrolysis is a potentially efficient method for recovering energy from sewage sludge: the products can provide a significant portion of the energy required by municipal wastewater treatment plants. For manure, energy production by pyrolysis is assumed to occur near markets for the recovered energy.

2 SLUDGE-CONVERSION SYSTEMS: PROCESS CHARACTERISTICS, ENVIRONMENTAL DATA, AND CAPITAL COSTS

2.1 ANAEROBIC DIGESTION OF MUNICIPAL SLUDGE

2.1.1 Process Characteristics

One of the advantages of anaerobic digestion is the simplicity of the processing equipment. The anaerobic sludge digestion plant consists of digesters and a filtration unit to dewater the digested sludge. Figure 2.1 is a flow diagram of the plant. As a basis for this plant model, a municipal center with population of about two million people was chosen. A conventional primary-secondary, activated-sludge digestion plant designed for 200×10^6 gallons per day (200 MGPD) -- 100 gallons per day per person -- is assumed to provide feedstock to the plant. The digestion plant will process 484,070 dry pounds of sludge per day, or 242 lb/day per 1,000 people. The solids are assumed to be 75% volatile.¹¹ Gas produced is medium-Btu (about 600 Btu/ft³), and, as suggested in Fig. 2.1, the model plant will burn a portion of the gas on site for internal power and heating needs. The balance of the gas, representing the net energy produced by the plant, will be used in the associated wastewater treatment plant. The energy production characteristics of the plant are summarized in Table 2.1. As shown there, 96 plants of this size could process sludge from 192 million people (if concentrated in suitably large cities) and produce 1 Quad (10^{15} Btu) of energy over a 20-year plant life.

Digesters. Thickened sludge from the wastewater treatment plant is fed to two-stage digesters at the rate of about 20,000 dry pounds per hour. The first stage is a complete-mix, high-rate digester, while the second stage further digests and decants the sludge. Volatile solids are reduced by

Table 2.1 Energy Production Characteristics of
Anaerobic Digestion of Sludge in the
Assumed System^a

Characteristic	Value
Input, Btu/hr	151.3×10^6
Net Gas Output, Btu/hr	59.4×10^6
Efficiency, %	39
Overall life, years	20
Energy produced over 20 years, Btu	1.04×10^{13}
Number of plants to produce 1 Quad over 20 years	96
Population to feed 96 plants	192×10^6

^aProcessing about 240 tons/day of sludge from
a 200-MGPD waste-treatment plant.

Fig. 2.1. Anaerobic Digestion of Municipal Sludge

Stream Identification

- ① Primary and Waste Activated Sludge--20,170 lb/hr solids at 7 wt% solids, 75% volatile. Represents energy input of 151.3×10^6 Btu/hr.
- ② Biogas-- 3.2×10^6 scf/day (gross), containing 61% CH_4 , 4% H_2 , 1% NH_3 , 0.5% H_2O , 0.5% O_2 ; 667 ppm H_2S ($1,000 \text{ mg/m}^3$).
- ③ Digester Supernatant--55,700 lb/hr, containing 500 mg/L BOD_5 and 150 mg/L suspended solids.
- ④ Digested Sludge--11,840 lb/hr solids at 7 wt% solids.
- ⑤ Filtrate--122,700 lb/hr containing 500 mg/L BOD_5 and 1,000 mg/L suspended solids.
- ⑥ Water Returned-- 3 plus 5 .
- ⑦ Cake--11,600 lb/hr solids at 25 wt% solids plus 34,800 lb/hr of water.

Energy Penalties: Heating and mixing primary digesters: 0.66×10^6 scf/day.
Filter operation at 10,000 Btu per hp·hr: 0.16×10^6 scf/day.

Net Biogas: 2.37×10^6 scf/day.

55% in the process, yielding a gross gas production of 3.2×10^6 ft³ of gas per day with a heating value of about 600 Btu/ft³. The digesters operate at about 95°F, which requires the burning of about 5.25×10^5 ft³ of the gas per day for heating.

Dewatering Filter. The digested sludge must be dewatered prior to final disposal. Sludge leaves the second stage digester at 6% solids by weight (wt %). Solids content is increased to 25 wt % by mechanical dewatering on a vacuum filtration device. The filtrate is returned to the water treatment plant, and the filter cake is collected and stored for ultimate disposal.

Materials. The amounts of steel and concrete required for all equipment in the plant are summarized in Table 2.2.

2.1.2 Environmental Data

Residuals and Effluents. The sulfur dioxide and nitrogen oxide emissions listed in Table 2.3 are not emitted from the digestion process but from subsequent burning of the gas for steam production. Much of the carbon dioxide, however, is formed during the digestion reaction and passes through the system. Sulfur dioxide emissions are estimated to range from 16 to 32 lb/hr: available data indicate a range of hydrogen sulfide (H₂S) of 1 to 2 grams per cubic meter of the digester gas. The high H₂S levels would be tolerable in steam boilers but may be corrosive in internal combustion motors, which might use digester gas at the treatment plant. The gas may therefore need scrubbing. The nitrogen oxide values were calculated from the assumed ammonia concentration in the biogas.⁶

Water will leave the digestion system as decanted supernatant at the second digester and as filtrate from the dewatering filters. These streams will be returned to the head of the waste plant and therefore may not enter the environment, but suspended solids and biochemical oxygen demand in the water are nonetheless accounted for in Table 2.3.

The amounts of heavy metal residuals shown in Table 2.3 are calculated from the assumed feedstock composition, but actual sludge composition and heavy metal content are highly variable among areas. Table 2.4 illustrates the variability reported in three data sources;^{2,12} the values chosen for this study are also indicated there.

Land and Water Use. About 5 acres of land would be required for the plant. Water use is negative, because large quantities of water are recovered from the sludge and returned to the waste plant for treatment.

Table 2.2 Amounts of Materials Required for the Sludge Digestion Plant Assumed^a

Component	Steel, Tons	Concrete, Yards
Digesters	1,000	8,000
Vacuum Filters	110	-
Filter Building	43	133
Total	1,153	8,133

^aProcessing about 240 tons/day of sludge from a 200-MGPD waste-treatment plant.

Table 2.3. Residuals from Anaerobic Digestion of 242 Tons/Day of Municipal Sludge Solids

Residual	Pounds Per Hour	Tons/Day	Millions of Tons Per Quad of Net Energy
CO ₂	5,108	61.3	42.9
SO ₂ ^a	16-32	0.2-0.4	0.14 - 0.28
NO _x ^a	17	0.2	0.14
Hydrocarbons	Nil	Nil	-
Particulates	Nil	Nil	-
Solids	11,582	139	97.15
Cadmium ^b	0.50	0.006	0.004
Chromium ^b	20.17	0.242	0.170
Lead ^b	20.17	0.242	0.170
Mercury ^b	0.20	0.002	0.002
Nickel ^b	4.03	0.048	0.034
Zinc ^b	50.42	0.605	0.424
Arsenic ^b	0.87	0.010	0.007
Silver ^b	4.54	0.054	0.038
Selenium ^b	0.52	0.006	0.004
Copper ^b	20.17	0.242	0.170
Biochemical Oxygen Demand ^c	131	1.57	1.10
Suspended Solids ^c	143	1.72	1.21

^aFrom combustion of H₂S and NH₃ in digester gas.

^bMetals in solid residue.

^cIn recovered water, which is returned to the waste plant for treatment.

Table 2.4. Reported Ranges and Means of Metal Concentrations (ppm) in Various Municipal Sludges

Metal	Commercia ^a		EPA ^b		Chaney ^c	
	Range	Mean	Range	Mean	Domestic Sludge (Mean)	Controlled Municipal Sludge (Mean)
Arsenic	6-230	43 ^d	10-50	9	-	-
Beryllium	-	-	e	e	-	-
Cadmium	3-3,410	110	0-1,100	87	5	25 ^d
Chromium	10-99,000	2,620	22-30,000	1,800	50	1,000 ^d
Copper	84-10,400	-	-	-	-	1,000 ^d
Lead	13-19,700	1,360	80-26,000	1,940	150	1,000 ^d
Mercury	0.2-10,600	733	0.1-89	7	2	10 ^d
Nickel	2-3,520	320	0-2,800	410	25	200 ^d
Selenium	-	-	10-180	26 ^d	-	-
Silver	-	-	0-960	225 ^d	-	-
Zinc	101-27,800	2,790	51-28,360	3,483	750	2,500 ^d

^aRef. 12.

^bRef. 20.

^cRef. 2.

^dValue assumed for feedstock sludge in this study.

^eNot detected; beryllium content was assumed to be nil.

Table 2.5. Construction Costs for a 200-MGPD
Anaerobic Sludge Digestion Plant

Component	Cost in 1972 Dollars			Total
	Materials	Transport	Labor	
Digesters, Primary (5)	432,500	16,500	1,093,500	1,542,500
Secondary (5)	432,500	16,500	1,093,500	1,542,500
Vacuum Filter and Filter House	595,550	20,660	343,790	960,000
Total	1,460,550	53,660	2,530,790	4,045,000

2.1.3 Capital Costs

A little over \$4 million (1972 dollars) would be needed for materials, transportation, and labor to build an anaerobic digestion plant of the size assumed. Table 2.5 shows the components of this cost. (Estimates are expressed in 1972 dollars, as required for use in the SEAS model.)

2.2 INCINERATION OF MUNICIPAL SLUDGE

The composition of sludge to be incinerated is assumed to be the same as that assumed for anaerobic digestion in Section 1 and Tables 1.1 and 1.2. The plant size assumed is, however, larger by one-third than the digestion plant. Thus, the incineration plant is assumed to process municipal sludge from a population of about 3 million people.

Table 2.6. Energy Production Characteristics of Sludge
Incineration in the Assumed System^a

Characteristic	Value
Input, Btu/hr	221.2 x 10 ⁶
Output, Btu/hr	82.5 x 10 ⁶
Efficiency, %	37
Overall life, years	20
Energy produced over 20 years, Btu	1.45 x 10 ¹³
Number of plants to produce 1 Quad over 20 years	69
Population to feed 69 plants	207 x 10 ⁶

^aProcessing sludge from a 300-MGPD waste-treatment plant.

Fig. 2.2. Incineration of Municipal Sludge.

Stream Identification

- ① Primary and Waste Activated Sludge--29,500 lb/hr solids at 5 wt% solids; 75% volatile. Represents energy input of 221.2×10^6 Btu/hr.
- ② Furnace Feed--30,250 lb/hr solids at 30 wt% solids, containing 22,115 lb of volatile solids and 8,135 lb of ash.
- ③ Ash--9,000 lb/hr.

Energy Penalties: Furnace heating: 800 bhp.
 Filter operation: 650 bhp.
 Miscellaneous losses: 150 bhp.

Net Energy Recovered: 82.5×10^6 Btu/hr.

2.2.1 Process Characteristics

Processing units for the sludge incineration system include dewatering filters, multiple-hearth furnaces, waste heat boilers, and flue gas scrubbers. A flow diagram of these units is shown in Fig. 2.2. The energy characteristics of the model incineration plant are presented in Table 2.6 (p.11).

Dewatering Filters. Filter presses are assumed to be used for dewatering. The filters increase the solids content of the sludge from about 4 wt% to 30 wt%. Ferric chloride and calcium hydroxide are added to the sludge before dewatering to aid in filtering. The sludge is dewatered to produce about 30,000 pounds of dry solids per hour, which requires 13 presses and about 650 brake horsepower.

Incinerators. Dewatered sludge enters the top hearth of the multiple-hearth furnace, where it is dried by hot combustion gases coming from the lower hearths. Sludge is burned as it moves downward through the hearths. Three multiple-hearth furnaces are required (one is held in reserve to allow an increase in operation when necessary). Each furnace has 12 stacked hearths with an internal diameter of 25.75 feet. To insure efficient burning, air is supplied at 75% above the stoichiometric requirement. To achieve a flue gas temperature of 1200°F, fuel is required at a rate equivalent to about 25.5×10^6 Btu per hour.

Waste Heat Boiler. Heat energy is recovered from the incinerator combustion gas in a waste-heat boiler at the rate of 89,000 pounds of steam per hour, at 700°F and 600 psi. The combustion gases are simultaneously cooled to about 200°F.

Scrubber. Multiple-hearth incinerators typically emit about 33 pounds of solids per ton of dry sludge feed.⁶ These particulates are controlled by wet scrubbing in a venturi scrubber, which reduces particulates in the flue gas by 96%. Particulate emission is thus reduced to about 1.3 pounds of solids per ton of dry sludge feed. The scrubbed flue gas is mixed with air that has cooled the incinerator and passed to the stack, where it is released to the atmosphere.

Materials. The amounts of steel, polypropylene (for the filter presses), concrete, and bricks required for construction of the incineration plant are summarized in Table 2.7.

2.2.2 Environmental Data

Residuals and Effluents. Operating wastes given in Table 2.8 are based on the feedstock characteristics described in Tables 1.1 and 1.2. Distribution of heavy metals in scrubber water, stack effluent, and ash is given in Table 2.9.

Table 2.7. Amounts of Materials Required for the Sludge Incineration Plant Assumed^a

Component	Steel, Tons	Polypro- pylene, Tons	Concrete, Yards	Bricks, Tons	
				Refractory	Insulating
Filter Presses (15)	675	225	-	-	-
Filter Building	86	-	266	-	-
12-Hearth Furnaces (3)	2,800	-	285	2,154	1,158
Total	3,561	225	551	2,154	1,158

^aProcessing municipal sludge from a 300-MGPD waste-treatment plant.

Table 2.8. Residuals from Incineration of 354 Tons/Day of Municipal Sludge Solids

Residual	Pounds per/hour	Tons/Day	Millions of Tons
			per Quad of Net Energy
CO ₂	41,235	495	250
SO ₂ ^a	35.2	0.422	0.21
NO _x ^a	70.3	0.844	0.43
Hydrocarbons	Nil	Nil	Nil
Particulates	19.2	0.230	0.12
Ash	8,982	107.8	54.4
Cadmium	0.72	0.009	0.0045
Chromium	29.0	0.348	0.174
Lead	29.0	0.348	0.174
Mercury	0.29	0.003	0.0018
Nickel	5.76	0.069	0.035
Zinc	72.6	0.871	0.435
Arsenic	1.24	0.015	0.0073
Silver	6.54	0.078	0.039
Selenium	0.76	0.009	0.0047
Copper	29.0	0.348	0.174

^aEstimated from EPA stack tests.

Table 2.9. Distribution of Metals in Sludge-Incineration Wastes, Per Quad of Energy Produced

Metal	Amount in Waste, Thousands of Tons			Total
	Scrubber water	Stack gas	Ash	
Arsenic	1.7	0.2	5.4	7.3
Cadmium	3.2	0.4	0.9	4.5
Chromium	9.3	4.5	130.4	174.2
Copper	9.7	4.5	129.3	173.5
Lead	8.6	8.9	86.7	174.2
Mercury	1.4	0.2	0.2	1.8
Nickel	7.9	0.9	25.9	34.7
Selenium	1.0	0.1	3.6	4.7
Silver	8.9	1.0	29.5	39.4
Zinc	195.7	21.7	217.1	434.5

Land and Water Use. As in the case of the anaerobic digestion plant, it is assumed that the incineration plant would be constructed near an existing municipal waste treatment facility. About one acre of land would be needed, and water use would be negative: large amounts of water would be returned to the waste plant for treatment.

2.2.3 Capital Costs

The capital cost of building an incineration plant that would process municipal sludge from 3 million people totals \$14,512,500 (1972 dollars). Table 2.10 shows the components of this cost.

Table 2.10. Construction Costs for a 300-MGPD Sludge Incineration Plant

Component	Cost in 1972 Dollars			Total
	Materials	Transport	Labor	
Multiple-Hearth Furnaces (3)	2,439,780	121,680	4,851,870	7,413,330
Filter Presses (15)	4,350,000	217,200	1,102,500	5,669,700
Filter House	120,000	10,000	60,000	190,000
Waste-Heat Boiler ^a	446,000	25,770	357,750	829,520
Scrubber	38,950	2,000	44,000	84,950
Stack	195,700	10,300	119,000	325,000
Total	7,590,430	386,950	6,535,120	14,512,500

^aIncluding equipment for feed-water treatment.

Fig. 2.3. Pyrolysis of Municipal Sludge

Stream Identification

- ① Primary and Waste Activated Waste Sludge--29,500 lb/hr solids at 5 wt% solids, 75% volatile. Represents energy input of 221.2×10^6 Btu/hr.
- ② Furnace Feed--30,250 lb/hr solids at 35 wt% solids, containing 22,115 lb of volatile solids and 8,135 lb of ash.
- ③ Ash--9,000 lb/hr.

Energy Penalty: Equivalent to 1,380 bhp.

Net Energy Recovered: 104.6×10^6 Btu/hr.

2.3 PYROLYSIS OF MUNICIPAL SLUDGE

2.3.1 Process Characteristics

Pyrolysis requires a sludge dewatering unit (filter presses), a pyrolysis reactor, a fuel gas afterburner, a waste heat boiler, and a flue gas scrubber. Such a system is being installed in Contra Costa County, California.¹² The process flow diagram in Fig. 2.3 shows the arrangement of these units. The fuel gas produced is immediately burned in an afterburner to produce medium-pressure (600 psig) steam, the energy content of which represents the energy yield of the process.

Nearly 47% of the energy content of sewage sludge is recovered for use in the water treatment plant. It is estimated that sludge produced by a population of 165 million people could produce a Quad of energy over 20 years, but because of the distribution of population, only 30% of this energy is economically recoverable. Energy production by pyrolysis is summarized in Table 2.11.

Dewatering Unit. Wet sludge is dewatered by pressure filtration to increase the solids content of the sludge from 5 wt% to 35 wt%. About 504,000 pounds of water per hour are rejected from the sludge. Thirteen filter presses, including two or three as spares, are required; the on-line power required for the filter process amounts to 530 brake horsepower.

Pyrolysis Reactor. Multiple-hearth furnaces similar to those used for incineration serve as pyrolysis reactors. The controllability and combustion efficiency of such furnaces are enhanced in this use as partial-combustion reactors.

Table 2.11. Energy Production Characteristics of Sludge Pyrolysis in the Assumed System^a

Characteristic	Value
Input, Btu/hr	221.2 x 10 ⁶
Output, Btu/hr	104.6 x 10 ⁶
Efficiency, %	47
Overall life, years	20
Energy produced over 20 years, Btu	1.83 x 10 ¹³
Number of plants to produce 1 quad over 20 years	55
Population to feed 55 plants	165 x 10 ⁶

^aProcessing sludge from a 300-MGPD waste-treatment plant.

The plant contains three furnaces, one of which is kept in reserve. Each has nine refractory hearths surrounded by an insulated steel shell about 23 feet in diameter. A rotating central shaft, cooled by air, bears rabble arms to mix the sludge with the hot gases and move it to the ports opening into the next-lower hearth. The temperature in the top hearths may be as low as 600°F, while the bottom hearths operate at about 1,500°F.

Dewatered sludge enters the furnaces at about 35 wt % solids, at a feed rate of 86,440 lb (wet) per hour; the fuel gas produced has a heating value between 100 and 150 Btu/ft³ -- rather low, because of the high content of nitrogen, water vapor, and carbon dioxide in the gas. This gas passes directly to the afterburner for energy production.

Fuel Gas Afterburner. The pyrolysis gas produced in the furnace is ignited in an afterburner, which increases the gas temperature from 825°F to 1,245°F. Air is fed to the afterburner in 40% excess over the stoichiometric amount required for combustion of the volatile solids in the sludge.

Waste Heat Boiler. Hot gases from the afterburner raise steam in a waste heat boiler -- about 88,000 pounds of steam per hour at 600 psig and 700°F. This steam represents a heat recovery rate of 113×10^6 Btu per hour. The plant consumes about 8×10^6 Btu per hour, resulting in a net yield of 47% of the energy contained in the original sludge.

Scrubber. This type of multiple-hearth furnace, when operated in the incineration mode, emits in the gas 33 pounds of solids per ton of feed. No data on emissions in the pyrolysis mode are available; the emission rate should be lower than from incineration, but presumably some solids will still be emitted. Therefore the flue gases from the afterburner must be scrubbed to remove about 96% of the solid particles, reducing the solid emissions to less than 1.3 pounds per ton of dry sludge. To accomplish this, the gas is put through a venturi scrubber operated at a pressure drop of about 20 inches of water.

Materials. Material requirements are summarized in Table 2.12.

2.3.2 Environmental Data

Residuals and Effluents. Residuals from sludge pyrolysis in a plant of the size assumed are summarized in Table 2.13. The distribution of metals between the ash, scrubber water, and flue gas is shown in Table 2.14. Emissions to air come from the afterburner. Nitrogen oxide emissions were calculated from data on nitrogen oxides produced from low- and medium-Btu gases. Sulfur dioxide emissions are based on EPA tests of sludge incineration facilities and the Contra Costa County, California, tests,¹⁶ which indicate that only a small percentage of the sludge sulfur is oxidized.

Land and Water Use. It is estimated that one acre of land would be required for the plant. Water use would be minimal or negative, as with the other processes discussed.

Table 2.12. Amounts of Materials Required for the Sludge Pyrolysis Plant Assumed^a

Unit Operation	Steel, Tons	Poly- propylene, Tons	Concrete, Yards	Brick, Tons	
				Refractory	Insulating
Filter Presses (13)	585	195	-	-	-
Filter Building	85	-	230	-	-
8-Hearth Furnaces (3)	1,869	-	180	1,440	771
Total	2,529	195	410	1,440	771

^aProcessing municipal sludge from a 300-MGPD waste-treatment plant.

Source: Refs. 13, 14.

Table 2.13. Residuals from Pyrolysis of Sludge from a 300 MGPD Treatment Plant

Residual	Pounds per Hour	Tons/day	Millions of Tons per Quad of Energy
CO ₂	37,097	445	177.3
SO ₂ ^a	35.2	0.422	0.17
NO _x ^b	48.2	0.578	0.23
Hydrocarbons	Nil	Nil	Nil
Particulates	19.2	0.230	0.10
Ash	8,982	107.8	42.9
Cadmium	0.74	0.009	0.0035
Chromium	29.49	0.354	0.141
Lead	29.49	0.354	0.141
Mercury	0.29	0.004	0.0014
Nickel	5.90	0.071	0.028
Zinc	73.72	0.885	0.352
Arsenic	1.27	0.015	0.0061
Silver	6.63	0.080	0.032
Selenium	0.77	0.009	0.0037
Copper	29.49	0.354	0.141

^aEstimated from EPA stack tests.^bCalculated.

2.3.3 Capital Costs

The capital costs of building a pyrolysis system to process municipal sludge from 3 million people total \$11,211,410 (1972 dollars). Table 2.15 presents the cost breakdown for the pyrolysis unit.

Table 2.14. Distribution of Metals in Sludge-Pyrolysis Wastes, Per Quad of Energy Produced

Metal	Amount in Waste, Thousands of Tons			
	Scrubber Water	Stack Gas	Ash	Total
Arsenic	1.4	0.2	4.5	6.1
Cadmium	6.5	0.3	0.7	3.5
Chromium	31.9	3.6	105.9	141.4
Copper	32.2	3.6	105.1	140.9
Lead	63.8	7.2	70.4	141.4
Mercury	1.1	0.2	0.2	1.4
Nickel	6.4	0.7	20.8	27.9
Selenium	0.8	0.1	2.8	3.7
Silver	7.4	0.8	24.5	32.7
Zinc	159.5	17.5	175.0	352.0

Source: Refs. 2, 15.

Table 2.15 Construction Costs for a 300-MGPD Sludge Pyrolysis Plant

Component	Cost in 1972 Dollars			
	Materials	Transport	Labor	Total
Filter Presses (13)	3,770,000	188,500	955,500	4,914,000
Filter House	120,000	10,000	60,000	190,000
Multiple-Hearth Furnaces (3)	1,829,850	91,260	3,414,000	5,335,110
Afterburner	284,400	14,900	202,700	502,000
Scrubber	30,900	1,600	31,800	64,300
Stack	132,500	7,000	66,500	206,000
Total	6,167,650	313,260	4,730,500	11,211,410

3 MANURE-CONVERSION SYSTEMS: PROCESS CHARACTERISTICS, ENVIRONMENTAL DATA, AND CAPITAL COSTS

As discussed in the Introduction, beef cattle at an average weight of 1,000 pounds produce 60 pounds of raw manure per head per day, containing 6.9 pounds of total solids, of which 5.9 pounds is volatile solids. Major beef-producing regions in the United States may have cattle populations in the range from 200,000 to 800,000 head within a 50-mile radius.⁵ In such regions, therefore, it would be possible to collect manure from about 145,000 cattle with an average haul distance of 25 miles. An anaerobic digestion system could draw on such a large supply of feedstock, but smaller systems would also be feasible: the one described below would process manure from 25,000 cattle. In contrast, pyrolysis systems are more capital intensive and offer economies of scale, particularly in the costs of pollution control equipment. Therefore the pyrolysis system to be described is scaled for the manure output of 145,000 cattle.

3.1 ANAEROBIC DIGESTION OF FEEDLOT MANURE

3.1.1 Process Characteristics

The assumed design of an anaerobic digestion plant for feedlot manure is based primarily on the flowsheet (Fig. 3.1) developed by Bio Gas of Colorado, Inc.¹⁰ This plant can process 0.2 lb/day of volatile solids per cubic foot of digester capacity. At 5.9 lb of volatile solids per day per animal, 25,000 head of cattle will produce 147,500 lb of volatile solids, which will require 737,500 ft³ of digester capacity. This capacity is supplied by three primary digesters 100 feet in diameter by 31 feet high. Three secondary digesters of the same size, with gas-holding covers, are also needed.

The digested sludge (42.5 tons of dry solids per day) is dewatered by 110-horsepower centrifuges,¹⁷ two on line and one in reserve. The extracted water goes to a controlled algae pond and later is returned to mix with raw manure entering the plant. The algae are harvested and dried as an animal feed supplement; the dewatered, digested residue is used as a fertilizer additive or solar-dried for animal feed.

Assuming a biogas production of 8.5 cubic feet per pound of volatile solids, this digestion plant would produce a gross yield of 1.25×10^6 cubic feet of gas per day.³ The digester gas is purified in an amine absorption step (see Fig. 3.1) to remove 35% of the CO₂ and most of the ammonia and hydrogen sulfide, resulting in gas with a heating value of 710 Btu/ft³. Although gas with this much CO₂ is not pipeline quality, it can be mixed with natural gas as an energy supplement. Removing more CO₂ by absorption could produce pipeline-quality gas, but the additional purification would consume much more energy. Removal of 35% of the CO₂ consumes 3.1×10^6 Btu/hr, which represents 10% of the total gas produced. (In some cases, it may be feasible to remove more CO₂. For example, Bio Gas, Inc. plans 50% CO₂ removal for a facility in Lamar, Colorado.)

Fig. 3.1. Anaerobic Digestion of Manure

Stream Identification

- ① Raw Manure--62,500 lb/hr at 11.5 wt% solids (7,188 lb/hr total solids) containing 6,125 lb volatile solids.
- ② Biogas-- 1.25×10^6 scf/day ($8.5 \text{ ft}^3/\text{lb}$ of volatile solids), containing 60% CH_4 , 38% CO_2 , 1% H_2S , 1% NH_3 . Gross gas heating value is 31.25×10^6 Btu/hr.
- ③ Digested Manure--3,542 lb/hr solids at 4 wt% solids.
- ④ Centrate--177 lb/hr of solids.
- ⑤ Coke--3,365 lb/hr solids at 25 wt% solids.
- ⑥ Product Gas--71% CH_4 , 29% CO_2 ; contains 710 Btu/scf.

Energy Penalties: Heating and mixing primary digester: 10×10^6 Btu/hr
 Centrifuge operation: 1.1×10^6 Btu/hr
 Gas purification: 3.1×10^6 Btu/hr

Net Energy Recovered: 17.1×10^6 Btu/hr; efficiency 28%.

Other major energy penalties within the digestion plant include 1.1×10^6 Btu/hr for the centrifuges and 10×10^6 Btu/hr for heating and mixing the primary digesters. Net energy production is 17.1×10^6 Btu/hr, a 28% efficiency overall. The net energy output from 25,000 head of cattle is roughly equivalent to 410,000 ft³ of natural gas per day. Energy production from the plant is summarized in Table 3.1.

Materials. The construction materials required are shown in Table 3.2, on the basis of construction practices common in municipal waste treatment.

Table 3.1. Energy Production Characteristics of Anaerobic Digestion of Manure in the Assumed System^a

Characteristic	Value
Input (Feedstock), Btu/hr	61.5×10^6
Ancillary Input, Btu/hr	14.2×10^6
Energy Production, Gross Btu/hr	31.3×10^6
Energy Production, Net Btu/hr	17.1×10^6
Efficiency, %	28
Overall life, years	20
Energy produced over 20 years, Btu	0.30×10^{13}
Number of plants to produce	
1 Quad over 20 years	333
Cattle to feed 333 plants	8.32×10^6
Gas Composition:	
Methane, vol. %	71
Carbon Dioxide, vol. %	29

^aProcessing 1.5×10^6 pounds of raw manure per day from 25,000 cattle.

Table 3.2. Amounts of Materials Required for the Manure Digestion Plant Assumed^a

Components	Steel, Tons	Stainless Steel, Tons	Concrete, Yards
Digesters	600	-	4800
Centrifuges (3)	4	7	-
Centrifuge			
Building	19	-	125
Auxilliary Equip.	2.3	-	-
Gas Purifiers	13.5	-	32
Total	638.8	7	4957

^aProcessing manure from 25,000 cattle.

Concrete tanks with steel covers are usually used, but Bio Gas of Colorado, Inc. is considering earthen basins lined with plastic, which should be appreciably less expensive.

3.1.2 Environmental Data

Residuals and Effluents. Table 3.3 summarizes the waste products from the anaerobic digestion plant. The only emissions to air are in the waste gas from regenerator off-gas. This gas contains CO₂, SO₂, and some NO_x; the amounts of SO₂ and NO_x shown in the table are calculated on an assumed concentration of 1% H₂S and 1% NH₄ in the raw biogas.¹¹ The CO₂ is simply stripped from the biogas.

The quantities of metals shown as residuals were calculated on the assumption that metals in the feedstock remain in the digested solids. Data on initial concentrations of heavy metals in manure are shown in Table 3.4; these appear to be the only data available on heavy metals in manure.⁹

Land and Water Use. About 3 acres of land will be required for the facility, mostly for the algae lagoon. Water requirements are minimal.

3.1.3 Capital Costs

About \$3 million (1972 dollars) would be needed to build an anaerobic digestion system to recover energy from feedlot manure from 25,000 head of

Table 3.3. Residuals from Anaerobic Digestion of Manure from 25,000 Cattle

Residual	Pounds per Hour	Tons/day	Millions of Tons per Quad of Net Energy
CO ₂	800	9.6	23.4
SO ₂ ^a	88	1.06	2.57
NO _x ^a	3	0.04	0.09
Hydrocarbons	Nil	Nil	Nil
Particulates	Nil	Nil	Nil
Solids	3,542	42.5	103.7
Lead ^b	0.333	0.004	0.010
Copper ^b	0.324	0.0039	0.0095
Iron ^b	20.83	0.250	0.609
Zinc ^b	2.42	0.029	0.071
Manganese ^b	2.50	0.030	0.073
Cadmium ^b	0.025	0.0003	0.0007
Aluminum ^b	19.42	0.233	0.568

^a Calculated.

^b All metals in solids.

Table 3.4. Metal Content of Manure in Various Stages of Digestion

Digestion Stage ^a	Content, ppm in Dry Solids						
	Pb	Cu	Fe	Zn	Mn	Cd	Al
First	42	33	3300	320	380	1.5	3100
Second	50	45	3600	240	380	2.7	3000
Third	52	80	3000	300	340	7.5	2700
Undigested	48	22	1800	480	280	1.4	1900
Average ^b	48	45	2900	335	345	3	2700

^aRefers to a three-stage digestion system rather than the two-stage system described in this study.

^bThese average values were used in this study to predict residual metal concentrations.

Source: Ref. 9.

cattle. Table 3.5 shows the breakdown of material, transport, and labor costs for the system.

3.2 INCINERATION OF FEEDLOT MANURE

A search of the literature did not reveal any useful references to the incineration of manure for energy recovery. Most efforts in universities as well as by industry and government agencies are directed toward anaerobic digestion or pyrolysis for energy from animal residues. Incineration yields net energy as hot gases or steam, which could be used in a sludge treatment

Table 3.5. Construction Costs for an Anaerobic Manure Digestion Plant

Component	Cost in 1972 Dollars			
	Materials	Transport	Labor	Total
Digestors, Primary (3)	156,000	6,000	393,000	555,000
Secondary (3)	156,000	6,000	393,000	555,000
Centrifuges (3)	283,800	13,200	43,500	340,500
Auxilliary Equip.	18,800	900	29,800	49,500
Centrifuge House	21,500	1,000	51,500	74,000
Gas Purifier	100,000	1,000	96,000	197,000
Algae System	529,400	23,900	626,700	1,180,000
Manure Dryer	59,200	3,600	61,700	124,500
Total	1,324,700	55,600	1,695,200	3,075,500

Stream Identification

- ① Semicomposted Manure--41,666 lb/hr of solids at 50 wt% solids, 37.8% C in solids. Represents energy input of 356.2×10^6 Btu/hr.
- ② Manure Drying--Gas from char combustor is cooled from 1750°F to 400°F as it dries the ground manure to 10 wt% water.
- ③ Pyrolysis Reactor and Char Combustor--58% of the C is pyrolyzed, yielding 13.7×10^6 scf/day of gas. Unreacted carbon goes on to the char combustor, where it burns to provide heat for maintaining the endothermic pyrolysis reaction (via transfer of hot sand) and for manure drying.
- ④ Ash--27.8% of the manure solids becomes ash, which has value as fertilizer.
- ⑤ Gas Conditioning--CO₂, H₂S, and NH₃ are removed from the gas, which loses 29×10^6 Btu/hr in the process.
- ⑥ Sulfur Recovery--4.5 tons/day of sulfur are recovered from the Stretford unit; the sulfur has value for fertilizer production.
- ⑦ Clean Gas-- 8.4×10^6 scf/day of gas containing 8% CH₄, 42% CO, and 48% H₂, with 387 Btu/scf.

Energy Penalties: Gas conditioning, 29×10^6 Btu/hr; sulfur recovery, 31×10^6 Btu/hr; incineration of waste gas, 94×10^6 Btu/hr; gas cooling and stripping, 11.5×10^6 Btu/hr; heat losses and reaction endothermy, 54.5×10^6 Btu/hr.

Net Energy Recovered: 135.4×10^6 Btu/hr as low-Btu gas, representing about 38% of energy input as manure.

plant but not to any great extent at a cattle feedlot. In addition, incineration leaves behind only ash, which does not have the considerable potential value of residues from anaerobic digestion of pyrolysis. For these reasons, incineration is not considered a useful method of energy recovery from manure and is not further addressed in this report.

3.3 PYROLYSIS OF FEEDLOT MANURE

3.3.1 Process Characteristics

The pyrolysis system assumed here would process manure from 145,000 cattle, or just under 1,000,000 pounds of total solids per day. The plant contains a manure dryer, a pyrolysis reactor and char combustor, a process-gas cooling train, equipment for CO₂ removal and sulfur recovery, condensate treatment apparatus, and waste gas incinerators. This system is similar to that conceived by Engler et al.;⁵ however, the CO₂ removal system is more consistent with industrial practice. Arrangement of these units is shown in Fig. 3.2. Energy characteristics of the model plant are given in Table 3.6.

Manure Drying. Semicomposted manure is brought to the plant containing 50% moisture. The manure must be ground to 60 mesh;⁵ a cage-mill flash-drying system can reduce the manure to this size and dry it at the same time by grinding it in the presence of hot gases from the char combustor. Drying is completed to 10% moisture content, as the gases transport the ground manure to the pyrolysis reactor pneumatically. At the same time, the gas is cooled from 1,750°F at the combustor exit to about 400°F. The wet gas is then sent to a flare stack where odors are removed by incineration before the flue gas is vented to the atmosphere.

Pyrolysis Reactor and Char Combustor. The manure is pyrolyzed in a fluidized-bed reactor. The pyrolysis reactor is a vertical, cylindrical pressure vessel with refractory-lined walls. A bed of sand stores heat and

Table 3.6. Energy Production Characteristics of Manure Pyrolysis in the Assumed System^a

Input, Btu/hr	356 x 10 ⁶
Output, Btu/hr	136 x 10 ⁶
Efficiency, %	38
Overall life, years	20
Energy produced over 20 years, Btu	2.38 x 10 ¹³
Number of plants to produce 1	
Quad over 20 years	42
Cattle to feed 42 plants	6.1 x 10 ⁶

^aProcessing 8.7 x 10⁶ pounds of raw manure (10⁶ pounds of solids) per day from 145,000 cattle.

promotes the contact of the manure particles with hot gas, maintaining a uniform temperature of 1,500°F at 60 psig. The high heating rates that result have been shown to maximize gas yields from the pyrolysis process. About 58% of the carbon in the manure is pyrolyzed, yielding 13.7×10^6 ft³ per day of gas with the composition shown in Table 3.7.⁵ This gas has a heating value of about 300 Btu/ft³. After carbon dioxide, ammonia, and hydrogen sulfide are removed, the heating value increases to about 350 Btu/ft³.

Unreacted carbon, along with sand entrained in the pyrolysis gas, is removed by high-efficiency cyclones. The dust-free gas is sent on to further processing, and the char and sand are pneumatically transported to the combustor.

Pyrolysis is an endothermic process, and heat is provided by combustion of unreacted carbon in the char combustor, which is also a fluidized-bed device. The heat required by the pyrolysis reactor is provided by circulating sand heated to about 1,750°F from the combustor to the pyrolysis reactor. Ash is blown from the bed, captured in a set of high-efficiency cyclones, quenched with cold water, and stored.

Process Gas Cooling. The pyrolysis gas is cooled in three steps. First, it is used to preheat the air fed to the char combustor to 500°F. An air flow of 79,000 lb/hr takes up about 7.5×10^6 Btu per hour, reducing the gas temperature to 600°F. The gas then goes to the 50-psig steam generator where it is cooled to 310°F, giving up approximately 2.3×10^6 Btu per hour. This step produces about 2,600 pounds of steam per hour. Finally, the gas is cooled to 100°F by circulating cold water in the quench tower, which removes 1.7×10^6 Btu per hour and purifies the gas of water-soluble contaminants (mainly ammonia). The cooled gas is treated to remove acid gases.

Acid Gas Removal. Acid gases (carbon dioxide and hydrogen sulfide) are absorbed in a packed column filled with monoethanolamine (MEA) in 10 wt% solution in water. This contact lowers the hydrogen sulfide content of the pyrolysis gas to less than 10 ppm and the carbon dioxide concentration to less than 50 ppm. The MEA circulation rate is approximately 425 gallons per minute.

Sulfur Recovery. The acid-gas-laden MEA stream is regenerated in the MEA stripper by reducing the pressure to about 56 psig and heating the solvent to 240°F. The heat input to the MEA stripper is about 31×10^6 Btu per hour. The regenerated MEA solution is cooled first by heat exchange with incoming MEA and then in a water cooler before recycling to the absorber column.

Table 3.7. Pyrolysis Gas Composition^a

Component	% by Volume ^b
Carbon Monoxide	33.3
Hydrogen	38.0
Methane	7.2
Carbon Dioxide	10.4
Hydrogen Sulfide	0.7
Ammonia	4.5
Water	5.8

^aVolume of gas produced is 13.68×10^6 ft³/day.

^bValues do not sum to 100% because of rounding

The gas stream released in the MEA stripper is approximately 7% by volume hydrogen sulfide. The hydrogen sulfide is removed in a Stretford unit, a two-stage absorber consisting of a venturi chamber and a packed column containing anthraquinone disulfuric acid (ADA). The hydrogen sulfide is converted to a reduced ADA-sulfur compound from which sulfur is recovered by blowing air through the solution; the sulfur precipitates and is recovered by filtration. About 4.5 tons of sulfur is recovered per day. The oxidizing air is sent to an incinerator.

Quench Condensate Treatment. A portion of the quench water used to cool the process gas in the final step is bled to the quench condensate treatment unit, which consists of an oil/water separator and an ammonia stripper. Although the pyrolysis reactor is expected to produce little oil, it is essential to the operation that oil not be allowed to accumulate. Heavy tars, char, and sand that might be in the quench water are also recovered and recirculated to the pyrolysis reactor.

Ammonia and hydrogen sulfide dissolved in the quench water are removed by boiling the water at about 5 psig. The recovered ammonia and hydrogen sulfide are sent to incineration, and purified water is rejected from the plant.

Waste Gas Incineration. All the waste gases from drying, sulfur recovery, and ammonia stripping are burned in separate incinerators. Each stream is mixed with sufficient fuel gas to allow an incineration temperature of 1,200°F when burned with 20% excess air. These incinerators represent a substantial energy penalty, equivalent to about 94×10^6 Btu per hour, or about 26% of the energy in the manure.

Materials. Material requirements for the construction of the pyrolysis system are given in Table 3.8.

3.3.2 Environmental Data

Residuals and Effluents. Waste products from the model plant are summarized in Table 3.9. Distribution of metals between the water, stack

Table 3.8. Amounts of Materials Required for the Manure Pyrolysis Plant Assumed^a

Component	Steel, Tons	Concrete, Yards	Steel Raschig Rings, Tons	Sand, Tons	Brick, Tons	
					Refractory	Insulating
Equipment	380	60	19	250	800	430
Building	60	125	-	-	-	-
Afterburner Assembly	280	70	-	-	-	-
Total	720	255	19	250	800	430

^aProcessing manure from 145,000 cattle.

emissions, and ash is given in Table 3.10. Stack emissions listed are associated with the waste gas incinerators; nitrogen oxides are calculated from data on low- and medium-Btu gases. Because most of the ammonia is removed in the quench tower, the emission of nitrogen oxides can be expected to be small.

Land and Water Use. One plant would need about 3 acres. Water usage is minimal; in fact, water will probably be produced from the plant in amounts that might be useful in an arid climate.

Table 3.9. Residuals from Pyrolysis of Manure from 145,000 Cattle

Residual ^a	Pounds Per Hour	Tons/Day	Millions of Tons per Quad of Net Energy
CO ₂	7650.0	91.8	28.1
SO ₂	0.75	0.009	0.00275
NO _x	69.6	0.835	0.256
Hydrocarbons	Nil	Nil	Nil
Particulates	Nil	Nil	Nil
Lead	2.00	0.024	0.007
Copper	0.92	0.011	0.007
Iron	75.00	0.900	0.444
Zinc	20.00	0.240	0.051
Manganese	11.67	0.140	0.053
Cadmium	0.06	0.001	0.005
Aluminum	79.17	0.950	0.413

^aCalculated

Table 3.10. Distribution of Metals in Manure-Pyrolysis Wastes, Per Quad of Energy Produced

Metal	Amount in Waste, Thousands of Tons			
	Water	Stack Gas	Ash	Total
Lead	3.3	0.4	3.7	7.4
Copper	1.6	0.2	5.1	6.9
Iron	100	11	333	444
Zinc	23	3	25	51
Manganese	23	3	27	53
Cadmium	0.33	0.04	0.09	0.46
Aluminum	93	10	310	413

3.3.3 Capital Costs

This is a capital-intensive system. Therefore a large installation is required to reduce the amortization payment part of the gas cost.⁵ Cost data are summarized in Table 3.11.

Table 3.11. Construction Costs for a Fluidized-Bed Manure Pyrolysis Plant

Component	Cost ^a in 1972 Dollars			
	Materials	Transport	Labor	Total
Pyrolysis Reactor	735,600	36,800	726,900	1,449,300
Vessels and Tanks	194,500	6,900	205,400	406,800
Columns	127,800	6,400	124,000	258,200
Pumps and Blowers	22,300	500	20,200	43,000
Exchangers	348,900	16,800	312,300	678,000
Misc. Equipment	705,400	31,400	703,200	1,440,000
Total	2,134,500	98,800	2,092,000	4,325,300

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4 DISCUSSION

The energy recovery systems described in this report would probably be sited near large sources of concentrated sludge or feedlot manure. In 1973, nine states -- Texas, Nebraska, Iowa, Kansas, Colorado, California, Illinois, Arizona, and Minnesota -- accounted for over 80% of the total number of cattle in U.S. feedlots.¹⁸ Several environmental impacts are associated with feedlots, especially those that collect the deposited manure only intermittently. Runoff from feedlot waste can severely lower dissolved oxygen levels in streams, producing biological oxygen demand and ammonia concentrations reaching 80 and 12 mg/L, respectively.³ Feedlots also contribute ammonia, amines, and odorous sulfur compounds to the atmosphere.³

Anaerobic digestion of manure does not degrade the fertilizer and soil conditioner value of the digested residue. The residue can, in fact, be dried and recycled as a proteinaceous livestock feed additive.¹⁹

Municipal sludge can be found in any metropolitan area. Medium and large urban areas have sewage collection systems and treatment facilities to which any of the conversion systems described could be added with little difficulty. Municipal sludge is generally considered a waste disposal problem, especially as competition for land increases and sanitary landfill sites become less available.

There are, however, major environmental constraints associated with these conversion technologies, in their potential for releasing atmospheric pollutants and heavy metals. Metropolitan areas produce large quantities of sludge, but they are also often categorized as nonattainment areas with regard to air pollution. Under EPA's emission offset policy, construction and operation of any new combustion facility in a nonattainment area will require more than an equivalent reduction in emissions from other sources in the area. An investigation of potential siting patterns and pollution conflicts is needed before energy recovery systems using municipal sludge can be considered as feasible energy supply sources.

Finally, fluidized-bed incineration deserves evaluation. Many municipalities are using such systems for sludge reduction, and it would be remiss not to analyze this process. The use of municipal refuse as a fuel supplement for sludge incineration should also be investigated. This scheme is being increasingly considered by municipal authorities concerned with waste disposal.

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