ENERGY RECOVERY FROM FEEDLOT MANURE:
AN ASSESSMENT OF ALTERNATE TECHNOLOGIES

by

John M. Sweeten, Ph.D., P.E.

Extension Agricultural Engineer-Waste Management

Texas Agricultural Extension Service

The Texas A&M University System

College Station, Texas 77843

Prepared for:

Research Committee

Texas Cattle Feeders Association

5501 West Loop I-40

Amarillo, Texas 79106

TABLE OF CONTENTS

ENERGY RECOVERY FROM FEEDLOT MANURE: AN ASSESSMENT OF ALTERNATE TECHNOLOGIES

by
John M. Sweeten, Ph.D., P.E.
Extension Agricultural Engineer-Waste Management
Texas Agricultural Extension Service
Texas A&M University System
College Station, Texas 77843

INTRODUCTION

Methods available for converting biomass such as feedlot manure into energy forms can be broadly classified as either biological or thermochemical conversion processes. Bioconversion processes utilize bacteria, enzymes, and/or algae. They include (1) anaerobic digestion for biogas or methane production, and (2) enzymatic fermentation for ethanol production. Thermochemical conversion processes use medium or high temperatures in the presence or absence of air. Steam and/or catalysts are sometimes added to speed up or increase the conversion rate. Examples of thermochemical processes for manure are direct combustion, pyrolysis, partial oxidation, and hydrogasification. General characteristics of biological vs. thermochemical processes are contrasted in Table 1 (Huffman 1978).

Relatively recent reviews of energy recovery processes for manure have been published by Huffman (1978), Walawender et al (1973a), and Kreis (1979). Several processes appear genuinely promising while others appear technically possible but grossly uneconomical. In the final analysis, the highest and best use for feedlot manure for most situations may continue to be as an energy replacement commodity (fertilizer or feedstuff) rather than as a fuel feedstock. Energy replacement value of feedlot manure relative to anhydrous ammonia or 18-46-0 dry fertilizer averages about 0.7 million BTU/ton of dry manure (Sweeten, et al, 1974). Utilization of feedlot manure as a feedstuff

TABLE 1

GENERAL COMPARISON OF FUEL GAS PRODUCTION APPROACHES*

ITEM	BIOCONVERSION (Anaerobic Digestion)	THERMOCHEMICAL (Pyrolysis or Partial Oxidation)
Process	Bacterial decomposition; low pressure, low temperature	Thermal decomposition; low or high pressure; high temperature
Product	High quality, 1,000 BTU/scf	Low-medium quality, 300 to 500 BTU/SCF
Hold Time	3 days or more	5 minutes or less
Feed Preparation	Add water, grinding	Dry (not all), grinding
Feedstock Problems	Metals, additives, age	None
Feedstock Available for conversion, weight basis	25% to 60%	50% to 90%
By-Product Residuals	40% to 75% of dry feedstock	10% to 30% of dry feedstock
Product Gas Quality, BTU/SCF		
- Raw Gas	500 to 600	250 to 350
- Final Gas Product	1,000	350 to 500
Raw Gas Yields, SCF/lb feedstock	3 to 7	6 to 20
Energy in Gas, BTU/lb of feedstock	1,550 to 4,100	2,150 to 5,100
Energy Yield, as % of feedstock**	17% to 50%	24% to 60%
COST, $MM BTU		
- No by-product credits	2 to 10	3 to 5
- With by-product credit for feedstuff	1 to 5	?
- Feedlot size, head	100,000	100,000

*Based on Huffman (1978).

**Energy in manure feedstock assumed to be 8,000 BTU/lb dry ash-free basis.

saves the energy otherwise needed to produce a replaceable feed ingredient. For example, if manure could be fed at 5% of the finishing ration replacing alfalfa, the net energy "savings" would be about 6.5 million BTU/dry ton (Sweeten, et al, 1974).

THERMOCHEMICAL PROCESSES

Most of the research on thermochemical processing of manure (as well as coal and municipal solid waste) has dealt with pyrolysis and partial oxidation. Pyrolysis is thermal decomposition of organic matter. It involves heating organic solids at a moderately high temperature and pressure in the absence of oxygen. Pyrolysis produces liquid and gaseous fuels and a solid residue. These products vary in amount and composition depending upon temperature, pressure, residence time, feedstock quality, and catalyst. While organic matter is broken down into simpler compounds, salts are concentrated in the solid fraction. Process equipment includes a heat source, a reaction chamber, and a system to separate the product gases, liquids (condensates), tars, char, and ash. Partial oxidation is almost identical to pyrolysis except that controlled amounts of air or pure oxygen are fed into the reactor. Commercial pyrolysis and partial oxidation processes include the following (Huffman, 1978):

- Purox®, Union Carbide
- Pullman-Kellog
- Lurgi
- Kopper-Totzek

Results of several research projects involving pyrolysis and partial oxidation of cattle manure were tabulated by the U. S. Environmental Protection Agency (Kreis, 1979). Compositions of liquid, gaseous, and solid products are given in Table 2.

Table 2. Characteristics of Raw Products From the Pyrolysis of Manure (From Kreis, 1979)

	Batch Pyrolysis			Continuous Pyrolysis	Oil Production	Hydrogasification		Ammonia Synthesis Gas		Cyclonic Burner	TCD-Char
	A	B	C	D	E & F	G	H	I	J	K	L
Ultimate Analysis of Feed, Wt.%											
Carbon	41.2	*	*	*	20.5	35.4	35.4	35.1-39.6	42.6	27.6	23.82
Hydrogen	5.7	*	*	*	2.5	4.2	4.6	5.3-5.9	5.5	3.76	3.80
Oxygen	33.3	*	*	*	14.5	23.5	30.1	0.0	23.7	21.48	*
Nitrogen	2.2	*	*	*	1.3	0.7	*	2.5-3.1	2.8	2.32	1.85
Sulfur	0.3	*	*	*	0.5	0.2	*	0.4-0.6	0.5	0.5	*
Ash	17.2	8.65	*	22.0	15.1	36.0	25.6	23.5-29.2	24.9	44.30	*
Yields (per ton of wet feed)											
Gas (Std. cubic feet)	13,940	104.4[a]	381[b]	16,610	*	.967[c]	*	8,400-15,000[d]	790[a]	16,208	*
Oil (bbl)	0.31	0.25	*	0.96	2.6	0.0	*	0.88[e]	0.14	1.0[c]	*
Waterphase (gal.)	38.3	222	*	89.5	*	.872[c]	*		42		*
Char (lb)	726	143	0.33[f]	526	*	40.6[g]	*	93	650	1,093	*
Oil Composition, Vol. %											
Carbon	*	*	*	*	78.6	*	*	*	*	*	*
Hydrogen	*	*	*	*	9.5	*	*	*	*	*	*
Nitrogen	*	*	*	*	4.2	*	*	*	*	*	*
Sulfur	*	*	*	*	0.37	*	*	*	*	*	*
Oxygen	*	*	*	*	7.3	*	*	*	*	*	*
Gas Composition, Vol. %											
Oxygen	0.0	0.0	4	1.72	*	0.0	0.0	0.3-2.5	0.0	3.5	*
Nitrogen	0.0	7	19	49.83	*	0.0	0.0	28.4-38.3	7.1	65.8	*
Carbon dioxide	24.5	37.2	18	14.06	*	33.5	16.11	13.1-18.7	14.2	22.5	*
Carbon monoxide	18.0	16.7	18	17.72	*	0.7	3.4	11.5-17.3	12.8	4.8	*
Hydrogen	27.5	16.4	30	10.2	*	11.3	10.56	18.1-26.2	27.4	2.2	*
Methane	22.7	15.5		3.07	*	42.1	18.55	6.2-7.9	32.3	0.6	*
Ethylene	0.0	0.4	13[h]	*	*	0.0	0.0	2.7-4.1	5.9	0.6	*
Ethane	0.0	1.7		*	*	12.4	5.38	<=0.3	0.4	*	*
Carbon	7.3	*	0.0	*	*	0.0	0.0	0.0	0.0	*	*
Water	0.0	*	0.0	*	*	0.0	45.85	0.0	0.0	*	*
Hydrogen Sulfide	0.0	*	0.0	*	*	0.0	0.15	0.0	0.0	*	*
Char, Wt. %											
Carbon	49.4	*	63	*	*	*	44.1	32.0-41.2	*	21.54	30.07
Hydrogen	0.4	*	*	*	*	*	1.6	0.3-1.6	*	1.07	1.49
Oxygen	0.4	*	*	*	*	*	0.0	*	*	*	*
Nitrogen	1.1	*	*	*	*	*	0.0	2.0-2.5	*	1.42	0.0
Sulfur	0.3	*	*	*	*	*	0.0	*	*	*	*
Ash	48.4	*	36	40	*	*	54.2	36.7-53.9	21.5	76.40	*
Heating Values											
Feed, BTU/lb. (dry)	7,110	*	*	7,630	*	*	*	3,194-3,739[i]	6,350	5,604	*
Gas, BTU/ft^3	450	4,200	1,900[j]	123	*	1,000+	*	*	*	*	*
Char, BTU/lb. (dry)	7,290	11,000	3,000	6,390	*	*	*	4,132-5,535[i]	*	2,011	*

A - Schlesinger et al. (1972)
B - Garner and Smith (1973)
C - White and Taiganides (1971)
D - Massie and Parker (1973)
E - Appell and Miller (1972)
F - Appell et al. (1971)

G - Kiang et al. (1973)
H - Feldman et al. (1973)
I - Halligan et al. (1974)
J - Huffman and Halligan (1974-75)
K - Natour et al. (1975)
L - Mackenzie (1976)

* Not reported
a - lbs/T of wet feed
b - mg/l
c - moles/80 gr.
d - H_2 + CO
e - bbl/ton of feed, oil plus waterphase

f - gr./gr. of total solids
g - gr./80 gr. feed
h - total combustibles and illuminants
i - Kg ccl/Kg
j - per lb of total solids

(References are from Kreis 1979)

Pyrolysis

Garner and Smith (1973) of the Midwest Research Institute performed laboratory scale pyrolysis of fresh cattle manure to determine product characteristics and optimum pyrolysis conditions to maximize production of liquid organic compounds. Maximum yields were obtained at temperatures of 400° to 500° C and low pressures. The liquid fraction contained a variety of alcohols, ketones, aldehydes, acids, amines, and phenols. Because considerable refinement would be necessary for recovery of individual components, this liquid was viewed as a fuel with a value similar to crude petroleum and coal tar from a coke oven. Pyrolysis of manure also produced a combustible gas with a heat content of 300 to 400 BTU/ cu ft. This gas contained hydrogen, methane, carbon monoxide, carbon dioxide, nitrogen, and traces of ethylene and ethane. The yield of this combustible gas mixture was equivalent to 2 to 3 million BTU/ton of dry manure. A solid residue (char) containing one-third ash and having unknown utility was also produced. Garner and Smith (1973) concluded that pyrolysis is uneconomical and that the fuels used to operate the system are probably more valuable than the products derived.

The liquification of cattle manure (as well as coal and municipal solid wastes) to produce an oil product was investigated on a laboratory scale by the U.S. Department of Interior's Bureau of Mines. At 380° C temperature and 6,000 psi pressure, cattle manure (45% moisture content) was reacted with carbon monoxide and steam to yield low sulfur oil (Appell, et al, 1972). Reaction time was 20 minutes. Addition of catalysts is not necessary. At optimum conditions, cellulose conversion was 99% and oil yield was 47%, or about two barrels of oil per ton of dry manure (Appell, et al, 1971). The oil contained 75% to 78% carbon, 9% hydrogen, and 13% to 15% oxygen, and had a heating value of approximately 15,000 BTU/pound. Hence, the energy yield was

9.9 million BTU/ton of dry manure. The economics of this process remain unproven (Anderson, 1972), or unattractive (Walwender, et al, 1973b). Fu, et al (1974) developed a variation of the Bureau of Mines system in which cattle manure was hydrogenated and liquified at pressures of 1,500 to 3,000 psi and temperatures of 330° to 425° C in the presence of recycled manure oil and a catalyst. Organic matter conversions of 93% to 97% were achieved and oil yields were 39% to 40%. The product oil had a heating value of 16,300 to 17,200 BTU/lb.

On a much larger scale, Knight, et al (1974) at Georgia Tech University built a 50 ton/day unit for pyrolysis of cellulosic agricultural wastes, primarily wood wastes and crop residues. Cattle manure was not tested. Two years of research showed that the moisture content of feedstock should be less than 10%, which necessitated predrying. Heat balance measurements revealed that 36% of the input energy was available in the char, 13% in the condensed oil, and 46% in the noncondensible gases. Heat loss was only 5%. Heating value of the product oil was 13,400 BTU/lb and of the char was 9,000 to 13,000 BTU/lb. At 600° C, product gases from cotton gin trash contained 14% methane, 14% hydrogen, 21% carbon monoxide, 44% carbon dioxide, and 7% assorted hydrocarbon gases (C_2, C_3, and C_4 complexes). As operating temperatures rose from 400° C to 700° C, the yields of oil and gas improved as the char yield decreased. These researchers recommended marketing a mixture of 70% char and 30% condensed oil. This mixture is low in sulfur, is easily handled as a solid, would make a good coal extender, and could be burned in existing facilities. System economics appeared favorable to the researchers.

Engler, et al (1975) at Kansas State University analyzed the economics of pyrolysis of feedlot manure for plant capacities ranging from 500 to 10,000 tons/day of manure at 50% moisture. Breakeven gas production prices dropped dramatically from 500 to 1,000 tons/day capacity and leveled off above 5,000 tons/day. Output of scrubbed synthesis gas (CO_2 and H_2S removed) from a 1,000 ton/day plant would be 10.7 million scf/day of gas containing 380 BTU/cu ft. Total capital investment (1974 costs) was estimated at $6.5 million. Manure predryers required to reduce moisture content down to 10% would account for one-third the capital cost. The gas cleanup system (water scrubber) would account for another one-third of the cost. Operating expenses were estimated at $2.2 million/year. Engler, et al (1975) concluded that pyrolysis plants can approach the point of competitiveness with natural gas only under the most favorable circumstances.

Partial Oxidation

Manure and other agricultural residues can be partially oxidized in the presence of steam and limited air to form a synthesis gas, which in turn can be converted to anhydrous ammonia (Halligan and Sweazy, 1972; Young, et al, 1973; Beck, et al, 1979). Organic matter in manure serves as a source of hydrogen which can be combined with nitrogen from the atmosphere for subsequent combination to form anhydrous ammonia. The reactor system studied at Texas Tech University (Figure 1) is three stories high and can process 0.4 tons/day. It was described by Beck, et al (1979), as follows:

> "Solid feed enters the top of the reactor and falls countercurrent to a gas mixture of steam, air, and product gases. Product gas from pyrolysis and partial oxidation exit (with input fluids) out the top of the reactor. The product gas is stripped of entrained solids, tar, and a water/organic mixture using a cyclone, impinger, and heat exchanger, respectively. Char is removed from the bottom of the reactor through a centerport opening in the inlet gas distributor."

The partial oxidation reaction takes place at atmospheric pressure and average reactor temperature of 550° to 600° C, with peak temperatures inside the reactor approaching 900° C (Beck, et al, 1979). The heated manure releases synthesis gas composed of hydrogen, nitrogen, methane, carbon monoxide,

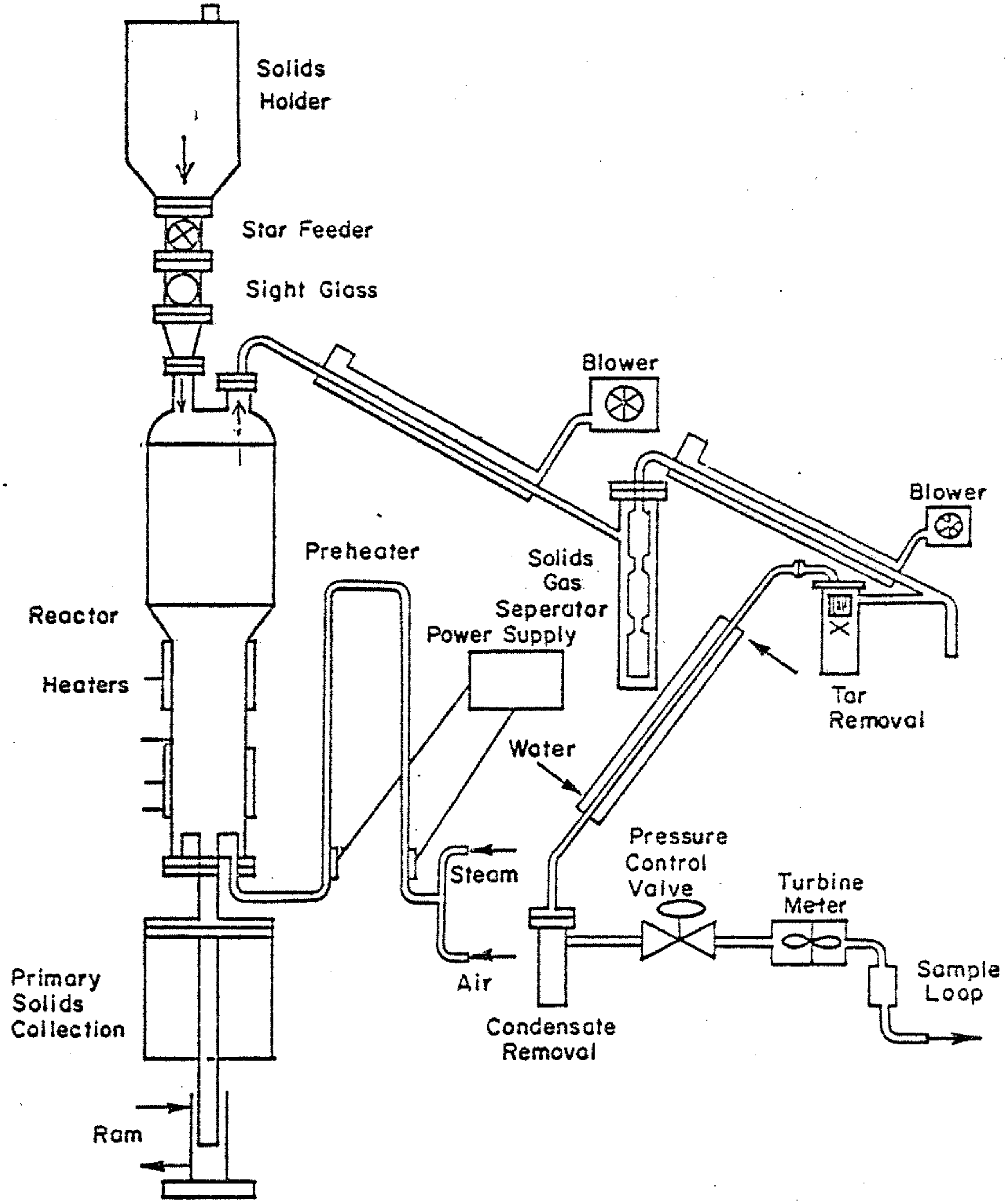

Figure 1. Schematic Diagram of Texas Tech Partial Oxidation/Synthesis gas Process (Kreis 1979)

carbon dioxide, ethylene, and ethane. Results from the 35 lb/hour pilot plant are shown in Table 3. The product gas is suitable as a synthesis gas for production of anhydrous ammonia, ethylene, or methanol, or as a medium BTU fuel gas for other processes.

High operating temperatures favor gas production and diminish yields of char and liquid residuals (Huffman, et al, 1977). The solid char has a heating value of approximately 13,000 BTU/lb. It could be burned on-site to generate steam and electricity to operate the syn-gas process. The organic liquid product could be recycled back to the reactor to improve hydrocarbon yield of the product gas (Huffman, et al, 1977). One-fourth of the manure feedstock could end up collected as fly ash which has indefinite value.

The ammonia synthesis gas would be fed to an existing anhydrous ammonia plant (of which surplus capacity exists in the Texas Panhandle) and used as a replacement feedstock for natural gas. The ethylene could be separated and sold as feedstock to a petrochemical company. At the ammonia plant, the carbon monoxide component is first reacted with steam to yield equal parts of hydrogen and carbon dioxide. The carbon dioxide is separated (and possibly sold). This leaves hydrogen and nitrogen in almost a perfect 3:1 ratio for combination as anhydrous ammonia (NH_3).

Heat balance calculations show that the overall partial oxidation reaction is exothermic (i.e. produces more energy that it consumes). The product synthesis gas stream contains 40% to 60% of the heating value of dry, ash-free manure (Huffman, et al, 1977). This raw gas contains about 240 BTU/cu ft, or 300 to 320 BTU/cu ft after removal of carbon dioxide. Gas production amounts to 10 to 20 scf/lb of dry ash-free manure. Thus, the gas heating value is about 6 million BTU/ton of dry manure.

TABLE 3

TYPICAL DATA FROM TEXAS TECH PARTIAL OXIDATION PLANT

(Huffman, 1978)

	Average of 5 runs*	Range
Feed Rate, lb/hr		
(25% ash, 10% water)	35	32 to 38
Air Feed Rate, scf/hr	124	70 to 212
Steam, lb/hr	11	10 to 14
Avg. Temperature, °C	602	577 to 636
Dry Gas Yield		
SCF/lb dry ash-free manure	15	10 to 20
BTU/scf	305	265 to 351
Raw Gas Composition (Vol. %):		
H_2 - Hydrogen	25	18 to 33
N_2 - Nitrogen	22	18 to 24
CH_4 - Methane	8	6 to 11
CO - Carbon Monoxide	13	11 to 15
CO_2 - Carbon Dioxide	27	24 to 31
C_2H_4 - Ethylene	4	2 to 7
C_2H_6 - Ethane	0.8	0.7 to 0.9

*Experimental Runs No. 21, 24, 28, 30, and 32.

The experimental data suggest that ammonia yield would exceed 0.5 tons NH_3/ton of dry, ash-free manure feedstock (Huffman, et al, 1977). An additional 0.08 tons of ethylene could be extracted per ton of dry ash-free manure. These products could together be worth $130/ton of dry ash-free manure, or $65/ton of as-received manure (30% ash, 30% moisture).

On an energy basis, if the process is adiabatic (heat production matches heat requirement) as reported, the net energy savings to society is equal to the energy now used for manufacture of anhydrous ammonia, or 39 million BTU's/ton of ammonia yield. Consequently, the synthesis gas-ammonia process could result in an energy savings to society of as much as 12 million BTU/ton dry manure processed.

Researchers at Texas Tech, assisted by an independent study by Bechtel Corporation, have established the minimum feasible plant size at 1,000 tons of dry manure per day. Only 20 locations in the U. S. have the requisite 300,000 head of cattle on feed within a 25 mile radius. Capital cost is estimated at $62 million (Beck, 1980). Annual operating cost would be $7.5 million assuming the manure costs $3/ton delivered. To make a 15% return on investment, anhydrous ammonia would have to sell for only $130/ton, which is less than today's market price. This does not include credits that could be available from sale of carbon dioxide, one of the process by-products.

Advantages of partial oxidation for synthesis gas/ammonia production include favorable energy balance and suitability of typical feedlot manure as a process feedstock. While high ash content is a liability, moisture content and manure age are not major constraints within normal limits. Other advantages include modest air and water pollution potential, reactivation of locally idle ammonia plant capacity, and high product marketability and utility (anhydrous ammonia). Process economics appear encouraging provided that a large enough plant can be built.

Chief limitations appear to be uncertainty of successful plant scale-up by factor of 2000:1 from pilot plant scale to the 1,000 tons (d.m.)/day level; high capital cost; and remaining concerns associated with feedstock pulverizing, reactor feeding, and solids separation from the gas stream.

Hydrogasification

Conversion of feedlot manure into methane by thermochemical means (hydrogasification) was examined by Feldman, et al (1973), Kiang, et al (1973), and Walawender, et al (1973b). Hydrogasification would be accomplished by the Hydrane process, developed by the Bureau of Mines for converting coal to pipeline quality gas (Feldman, et al, 1973). The process involves decomposition of cellulose in the presence of hydrogen under conditions of high pressure (1,000 psi) and temperature (550° C). The hydrogen gas would need to be purchased and amounts to 6.5% of the dry manure input. Final product gas after CO_2 scrubbing consists primarily of methane, ethane, and hydrogen and has a BTU content of over 1,000 BTU/SCF. With further refinement, a gas consisting of 79% methane and 19% ethane can be produced (Feldman, et al, 1973). Manure feedstock must be predried and ground before introduction into a fluidzed bed reactor. Residence time is 2 seconds. The reactor is highly exothermic (produces heat) and does not require a catalyst (Walawender, et al, 1973a). Gross methane yield is 12,000 cu ft per ton of dry manure and the net methane yield is 5,300 cu ft/ton of dry manure (Walawender, et al, 1973b).

No tars or oils were produced from manure hydrogasification (Kiang, et al, 1973). The char by-product consisting of 45% of the dry manure feedstock was used as a boiler fuel (Feldman, et al, 1973).

This process would possibly have an economic advantage over coal gasification because it operates at lower temperatures and manure could presumably be delivered cheaper than coal (Feldman, et al, 1973; Kiang, et al, 1973). A minimum plant size of about 1,000 tons/day should be considered (Walawender, et al, 1973b).

Hydrogasification is not economically feasible (Walawender, et al, 1973b). Results from laboratory scale tests conducted so far would be difficult or impossible to extrapolate to the minimum feasible size of hydrogasification plant.

Direct Combustion

Feedlot manure can be burned in a cyclonic of fluidized bed furnace to produce steam for generation of electricity or for other purposes. Beck, et al (1979) estimated that heating energy potentially available annually from combustion of feedlot manure exceeds that from a managed forest and approaches the energy yield from a modest oil field, on a surface area basis. Published research on combustion of feedlot manure is lacking. However, broad estimates of the combustion potential can be made from experimental data and information concerning coal-fired electric power plants.

A study conducted at Swisher County Cattle Company in October 1979 to evaluate the combustion potential of feedlot manure (Sweeten and Higgins, 1980) determined that feedlot manure in the collected layer had an average heat value of 8,800 BTU/lb on a dry ash free basis. Ash and moisture have the effect of diluting the BTU content. Thus, feedlot manure containing 25% moisture and 30% ash would have a heat content of 4,600 BTU/lb (9.2 million BTU/ton) on an as-received basis, or 12.3 million BTU/dry ton.

The efficiency of converting manure or similar fuels (coal or lignite) into electricity is expected to be about 30% for a large coal fired power plant (Ladd, 1980). That is, it would take 11,400 BTU of fuel input to yield one kilowatt-hour (or 3,413 BTU) of electricity. For a small feedlot-sized boiler, only 20% efficiency might be realized (i.e. 17,100 BTU input/kilowatt-hour output). Thus, the net energy output/ton of dry manure would be approximately 3.6 and 2.4 million BTU/ton for utility and on-site boilers, respectively (Table 4).

TABLE 4
ESTIMATED ENERGY OUTPUT FROM COMBUSTION OF FEEDLOT MANURE

	Large Electric Utility	On-site Boiler/Generator
1. Manure Energy Input, BTU/ton (d.b.)	12.3 million	12.3 million
2. Conversion Efficiency, %	30	20
3. Electric Energy Output, BTU/ton (d.b.), kw-hr/ton (d.b.),	 3.7 million 1,080 million	 2.5 million 720 million
4. Value of Electricity Output (@ 2¢/kw-hr fuel charge), $/ton (d.b.)	$21.60	$14.40

Selling manure feedstock to a public utility for direct combustion would appear attractive to some feedlots because of steady market potential and low capital and operating cost. On-site combustion for steam and for electricity generation by a feedlot would require capital expenditures, operating costs, inefficiencies due to intermittent usage, and a new or modified air pollution abatement permit (state and/or federal depending upon system size).

A multi-fuel boiler could convert feedlot manure to steam with about 80% thermal efficiency (Kolb, 1980). A 450 horsepower boiler providing 16,000 lbs. steam/hour would require approximately 1.5 tons of feedlot manure (w.b)./hour as fuel. Ash removal from the boiler could pose problems.

High sulfur content could limit the use of feedlot manure as a combustion fuel. This is because sulfur dioxide is classified as a "criteria pollutant" under the Federal Clean Air Act. The Texas Air Control Board allows existing fossil fuel combustion plants to emit up to 1.2 lbs SO_2/million BTU burned (or 0.6 lbs S/million BTU). New emissions sources have to meet tougher environment standards that require scrubbing of 70% to 90% of the sulfurous gases.

TABLE 5

COMPARISON OF TYPICAL WYOMING COAL WITH TEXAS FEEDLOT MANURE

Parameter	Western Coal	Feed Lot Manure*
Moisture Content, %	25	27
Ash Content, %	5	30
Heat Content, BTU/lb (w.b.)	8,500	4,400
BTU/lb (d.b.)	11,300	6,000
Sulfur Content, % (w.b.)	0.40	0.56
lbs/million BTU	0.47	1.30

*Sweeten and Higgins (1980).

Feedlot manure contains much more sulfur and ash than western coal (Table 5). To control sulfur dioxide and fly ash emissions, the furnace for burning manure should have a wet scrubber (rather than baghouse-type) emissions control system (Plunk, 1980).

Feedlot manure could possibly prove to be a viable feedstock when blended at approximately 10% manure to 90% coal. According to Ladd (1980), question marks include delivered cost, consistent supply, consistent composition (ash, sulfur, BTU), and combustion residue effects on the furnace (scale, slag, corrosion, abrasion, plugging, etc.). Salts and silica may cause corrosion and abrasion. The emissions problem in ash-fusion temperatures for feedlot manure need further evaluation. Public research on these effects has not been conducted.

The Harrington Station coal-fired power plant near Amarillo, owned by Southwestern Public Service Company, operates three 360 megawatt (MW) generators powered by low-sulfur coal from Gillette, Wyoming. Each unit burns up to 200 tons/hr. At 60% annual capacity factor the average coal consumption would be 360 tons/hour, or 8,640 tons/day (Yager, 1980). Only one 360 MW generating unit at Harrington Station has a wet scrubber system for emissions control (Plunk, 1980). The present delivered cost of coal is believed to be $25/ton. After stockpiling, conveying, crushing, and grinding, the pulverized coal is blown into the furnace at a cost of $1.65/million BTU's ($28/ton). The company is building a new coal-fired power plant, Tolk Station, scheduled for completion in 1982, in northwestern Lamb County. This plant will have two 543 MW generating units served by baghouse emissions control units and will require approximately 10,000 tons/day of coal.

Ladd (1979) suggested that the delivered price of biomass fuel would have to be about half that of coal in order to justify the associated risks and expected difficulties. According to current freight rates (Texas Railroad Commission, 1980) the cost of delivering feedlot manure in 23 ton loads from Hereford to either Harrington Station or Tolk Station (65 miles) would be $7.20/ton. If the manure can be collected, stacked, stockpiled, and loaded for $3/ton at the feedlot, the total delivered cost to the power plant would be $10.20/ton, or about $1.20/million BTU.

Ash-fusion temperature tests are used to determine abrasion, corrosion, slagging, scaling, and plugging problems inside the furnace caused by salts and silica. Two feedlot manure-oil mixtures (84% manure and 16% oil) subjected to ash fusion tests gave these results (Ladd, 1980):

a) Initial deformation temperature = 1900° F.
b) Softening temperature = 2280° to 2300° F.
c) Hemispherical temperature = 2300° to 2330° F.
d) Fluid temperature = 2360° to 2370° F.

According to Parker (1980) these temperatures appear to be high enough not to prove troublesome.

BIOCONVERSION FOR METHANE PRODUCTION

Bacterial digestion of manure under anaerobic conditions releases biogas which contains 50% to 60% methane, 40% to 50% carbon dioxide, and 1% trace gases such as hydrogen sulfide. Methane (CH_4) is the primary component of natural gas and has an energy content of 1,000 BTU/cu ft. Raw biogas has an energy content of 500 to 600 BTU/cu ft. Carbon dioxide can be removed to increase the BTU content.

Anaerobic digestion is a two-phase process. In the first phase, bacteria degrade (liquefy) organic solids into organic acids. In the second phase bacteria convert organic acids into methane, carbon dioxide, and water. A methane production system consists of these steps:

1. Materials preparation--grinding, mixing, pumping.
2. Digestion--reactor with agitation and heat exchange equipment.
3. Gas scrubbing--removal of moisture, hydrogen sulfide, and/or carbon dioxide.
4. Gas storage, on-site utilization or marketing.
5. Feedstuffs recovery--screening, centrifigation and drying.
6. Fertilizer recovery--storage pond and irrigation system.

Anaerobic Digester Types

Anaerobic digesters can be classified according to temperature, degree of mixing, and construction materials. Optimum operating temperatures are 95° F (mesophilic) and 135° F (thermophilic). Thermophilic digesters provide peak methane yields and are only one-third or one-half as large as mesophilic digesters. Mesophilic digesters cause fewer operating problems (Maciel, 1979).

In most digesters, slurry is mixed intermittently to renew bacterial contact with food and release biogas. The so-called "plug flow" digester recently developed at Cornell University employs no mixing device.

Digester Design

A major design factor is hydraulic retention time, or days of storage capacity. Correct design involves selecting the best trade-off between gas yield, which begins to level off after 10 days, digester size and construction cost. For mesophilic systems, retention times of 12 to 20 days are used. For thermophilic systems, retention times are only 5 to 6 days (Hamilton Standard, 1978; Hashimoto, et al, 1979b).

A second design factor is solids concentration, which dictates digester size, performance and cost. To minimize digester size, concentrations should be as high as possible without causing mixing problems or overloading. Desirable concentrations of total solids (ash plus organic matter) are 8% to 12%.

A third factor is loading rate, which is usually specified in terms of the weight of volatile solids (VS) added to the digester daily/unit of digester volume. Typical loading rates are 0.2 to 0.3 lbs VS/day/cu ft for mesophilic digester and 1.0 lb VS/day/cu ft for thermophilic digesters.

Anaerobic digester sizes for feedlots of 5,000 to 100,000 head capacity are estimated in Table 6 (Sweeten, 1979) which shows that a 10,000 head feedlot would build a mesophilic digester of approximately 1.1 million gallons.

TABLE 6

ANAEROBIC DIGESTER SIZE FOR CATTLE FEEDLOTS - MESOPHILIC

Feedlot Size Head	Volatile Solids Lbs/Day	Volatile Solids Concentration %	Slurry Inflow Gal/Day	Detention Time, Days	Total Digester Si 1,000 Gal
1,000	4,500	8	7,000	15	100
5,000	22,500	8	34,000	15	500
10,000	45,000	8	67,000	15	1,100
20,000	90,000	8	135,000	15	2,100
30,000	135,000	8	200,000	15	3,200
40,000	180,000	8	270,000	15	4,300
50,000	225,000	8	340,000	15	5,300
75,000	340,000	8	510,000	15	8,000
100,000	450,000	8	670,000	15	11,000

Gas Yields

The methane production rate (gas produced per unit of digester volume) gives an indication of digester performance. Methane production rates of 1.0 cu ft methane/cu ft/day for mesophilic digesters and 3.8 cu ft/cu ft/day for thermophilic digesters are typical.

Methane yield is a measure of both waste degradability and digester efficiency. Methane yields from dirt surfaced feedlot manure usually range from 2.5 to 4 cu ft CH_4/lb of volatile solids added to the digester, or about 8 cu ft of methane (13 cu ft of biogas)/lb of volatile solids destroyed.

TABLE 7

ESTIMATED PRODUCTION OF METHANE, FEEDSTUFFS AND FERTILIZER ELEMENTS FROM CATTLE FEEDLOT MANURE

Feedlot Size Head	Gross Yield		Net Methane Yield	Cattle Feed (Dry Basis)	Fertilizer Elemen Tons/Day		
	Biogas	Methane					
	1,000 Cu Ft/Day		1,000 Cu Ft/Day	Tons/Day	N	P_2O_5	K_2
5,000	130	80	53	5	0.2	0.2	0.
10,000	260	160	110	10	0.4	0.4	0.
20,000	525	320	210	20	0.9	0.8	1.
30,000	790	470	320	30	1.3	1.2	1.
40,000	1,050	630	420	40	1.8	1.6	2.
50,000	1,300	790	530	50	2.2	2.0	3.
75,000	2,000	1,200	790	75	3.3	3.0	4.
100,000	2,600	1,600	1,110	100	4.4	4.0	5.

Assumptions:

1. Volatile solids collected is 4.5 lbs/head/day.
2. Biogas contains 60% methane and 40% carbon dioxide (volume basis).
3. Methane yield is 3.5 cu ft CH_4/lb volatile solids feedstock.
4. Energy requirement for heating and mixing the digester is 25% of gross biogas output.
5. Feedstuff recovery is 2.0 lbs/head/day.
6. Recoverable fertilizer amounts before storage losses are 16 lbs N, 14 lbs P_2O_5, and 22 lbs K_2O/ton of manure feedstock.

Gas yields from a ton of cattle feedlot manure containing 30% moisture and 30% ash should be about 3,600 cu ft methane/ton. However, about 25% of the methane will be needed to provide digester heat (year around average). Thus, the net yield of methane will average about 2,700 cu ft/ton of feedstock (as received basis), or 3.8 million BTU/ton of dry manure. The amount of methane, feedstuffs, and fertilizer elements expected from different sized feedlots is shown in Table 7 (Sweeten, 1979).

Gas Scrubbing and Utilization

The degree of biogas scrubbing depends upon the ultimate use of the gas (Hashimoto, et al, 1979a). For on-site combustion as boiler fuel, only water vapor and hydrogen sulfide need to be removed from biogas. Water vapor is removed by frost proof condensers and condensate traps to prevent condensation in gas lines and excessive corrosion. Hydrogen sulfide causes corrosion and can be removed using an iron sponge (i.e., column of iron-impregnated wood chips) to a sufficient degree to allow biogas use in internal combustion engines (Fulton, 1979). Additional H_2S removal is necessary if the gas is to be sold to natural gas pipeline companies.

Carbon dioxide (CO_2) removal is necessary to produce pipeline quality methane (1005 BTU/cu ft). It can be removed by water scrubbing, membrane separation, phosphate buffer, or regenerative amine absorption (Ashare, et al, 1978). Water scrubbing is the most economical method. The heated (regenerative) amine absorption process is used at the Thermonetics, Inc. plant near Guymon, Oklahoma (Meckert, 1978). General Electric has developed a selective membrane process (Walmet, 1979) that is being tested in connection with the Imperial Valley Biogas Project at Brawley, California.

Biogas scrubbing equipment would account for 30% of the total cost of the methane production system for a 10,000 head feedlot if pipeline quality is desired (Hashimoto, et al, 1979a). But for on-site use of biogas, scrubbing equipment would cost only 10% to 12% of the total system cost.

Methane can be used as boiler fuel to operate steam flakers. Feed processing at a 30,000 head feedlot would require about 93,000 cu ft of methane/day for heat and 77,000 cu ft/day for electricity (at 22% conversion efficiency with internal combustion generator). This leaves a possible surplus of roughly 150,000 cu ft of methane, or 9,700 kw hrs of electricity to sell each day (Sweeten, 1979). Waste heat from the internal combustion engine can be used for slurry heating, thus increasing net methane yield (Hashimoto, et al, 1979a; Fischer, et al, 1979).

Five alternate strategies for feedlot biogas utilization and marketing were evaluated by Hashimoto, et al (1979a). The most economical strategies for on-site use were as follows:

1. Electricity generation after gas scrubbing (CO_2, H_2S, and moisture removal); gas compression to 125 psi; one-day storage capacity; waste heat recovery from internal combustion engine.
2. Electricity generation after H_2S and moisture removal, without compression or storage (CO_2 not removed); waste heat recovery from engine.
3. Boiler fuel, after H_2S and moisture removal; compression to 125 psi; and one-day storage.

Feed and manure trucks with gasoline engines can be equipped with a dual fuel carburetor to operate on bottled methane for about 2 hours/refill, or 3 to 4 gallons of gasoline equivalent (Heurich, 1979). Four feed trucks would use less than 10,000 cu ft of methane/day.

Feed Value of Centrifuged Slurry Cake

High protein feedstuffs can be extracted from the digested slurry. The crude protein content of this product ranges from 18% to 28% and averages about 25% (Maciel, 1979; Burford, et al, 1979; Hamilton Standard, 1978).

Meckert (1978) indicated a 50% removal of digested solids from the Calorific plant by centrifugation. Burford, et al, (1979) obtained 89% suspended solids recovery by centrifugation in the presence of a floculating compound. Hashimoto, et al (1978) recaptured 20% of the protein and 35% of the solids from digested slurry using a centrifuge. But by sieving the slurry with a #60 mesh sieve followed by centrifugation at 10,000 G for 20 minutes, 63% of the solids and 41% of the protein were captured. Crude protein content of the recovered solids was 12.5% for the sieved solids and 28% for the centrifuge cake, indicating that the high protein biomass is in the finer solids. At 50% recovery rate, about 2 lbs of feedstuffs (dry matter basis) could be obtained/head/day.

The centrifuge cake contains 70% to 80% moisture content. Attempts to feed this product wet have resulted in cattle palatability problems (Maciel, 1979). Burford, et al (1979) also cited decreased palatability of rations containing centrifuge cake.

Research at Oklahoma State University (Zinn, et al, 1979) showed relatively low nutritional value to a mixture of screened manure fiber extracted before digestion and the centrifuge cake mixed in about 2 or 3:1 ratio. The low digestibility and palatability that occurred is believed to be caused by the low nutritional value of the fiber screened from raw manure which dilutes the high-protein centrifuge cake.

Other research has revealed feedstuff values ranging from $25 to $90/dry ton (Hashimoto, et al, 1979b; Prokop, 1979; Burford, et al, 1979). Feedlot cattle feeding trials with centrifuge cake underway at Brawley, California, have tentatively established that the air dried product has the energy value of alfalfa (Prokop, 1979).

The dollar value of animal feedstuffs (digested slurry cake) is estimated at 2 to 5 times the methane value. Assuming only 20% solids recovery efficiency, the centrifuge cake is worth $16/head/year, while the methane is worth

$7/head/ year (Hashimoto, et al, 1979b; Hamilton Standard, 1978).

Fertilizer Utilization

Essentially all the plant nutrients originally present in the feedlot manure are captured in the digester slurry. Thus, the amount of land needed for disposal could conceivably be about the same as with dry manure, with the added complication of liquid pumping and distribution. However, nutrient recovery by centrifugation, nutrient losses in a holding pond by nitrogen volatilization and precipitation, and the recycle of liquids for slurry mixing can reduce the land area requirements by 50% to 80%. Research at Texas A&M University has shown a 50% loss of nitrogen in 72 days of storage of digested slurry in a holding pond (Egg, 1979).

Cost of Methane Production System

For methane production to be practical, the cheapest digester that will reliably produce biogas at acceptable levels is a necessity. Rigid wall, above-ground mesophilic anaerobic digesters, complete with slurry and gas handling systems, typically cost about $5 to $10/cu ft of digester capacity. Thermophilic units cost $5 to $20/cu ft, depending upon their size. Cornell and New Mexico State Universities have each fabricated digesters of flexible membrane liner installed in a trench (Hayes, et al, 1979; Kemp, 1978). These digesters reduce total system cost to about $3 to $7/cu ft. They have not been tested using dirt surfaced cattle feedlot manure or on a large scale.

USDA researchers at Clay Center, Nebraska published detailed cost projections for recovery of methane and protein from cattle feedlot manure by anaerobic digestion (Hashimoto, et al, 1979b). Feedlot size has a dramatic effect on cost. It is much cheaper per unit capacity to build a methane plant for 100,000 cattle ($66/hd) than for only 1,000 head ($370/hd). However, most of the cost difference occurs between the 1,000 and 25,000 head size levels.

SUMMARY

Several biological and thermochemical processes were examined for deriving energy value from feedlot manure. On the basis of data derived from research reports, it appears that energy output from these processes would be roughly as follows:

	Technology	Main Product	Yield Million BTU/ ton d.m.	Est. Cost for 20,000 hd.	
				Cap. Cost million $	Ann. Cost million $/
1.	Pyrolysis	Medium BTU gas mixture	2 - 3	2.3	0.8
2.	Pyrolysis	Oil	10	7.6	2.7
3.	Partial Oxidation	Synthesis gas (fuel)	6		
4.	Partial Oxidation	Synthesis gas/anhydrous ammonia	12	11.5	1.4
5.	Hydrogasification	Methane	5.3	3.1	1.1
6.	Direct Combustion				
	a. Utility Scale	Steam/Electricity	3.6		
	b. On-Site Furnace/ Generator	Steam/Electricity	2.4	0.5	
7.	Anaerobic Digestion	Methane or biogas	3.8	2.2	0.6

Estimates of capital and operating costs for various systems were calculated for a 20,000 head feedlot by updating cost estimates of the original investigators to 1980 prices using the Chemical Engineering Plant Cost Index[1/]. These costs were then scaled down to an operating capacity of 90 tons manure/day (as received basis) using the six-tenths power function[2/]. The resulting cost figures, some of which are tenuous at best, are shown in the preceding table.

[1/] Chemical Engineering Plant Cost Index: 1973--144.1; 1974--165.4; 1975--182.4; 1976--192.1; 1977--204.1; 1978--218.8; 1979--238.7; 1980 (Feb.)--250.7.

[2/] Six-tenths power function: $(\text{Cost})_2 = (\text{Cost})_1 \; {\frac{(\text{Plant Size})_2}{(\text{Plant Size})_1}}^{0.6}$

Of the manure conversion processes considered, it appears that direct combustion, partial oxidation, and anaerobic digestion offer the most possibilities at this time. The former two appear most uniquely adapted to the quality of manure collected from Texas cattle feedlots. Materials handling problems associated with ash content, and in some cases sulfur and salt, are common to essentially all these processes.

REFERENCES

1. Anderson, L. L. 1972. Energy Potential from Organic Wastes: A Review of the Quantities and the Sources. IC-8549, Bureau of Mines, U. S. Department of the Interior, Washington, D.C. 16 p.

2. Appell, H. R., S. Friedman, Y. C. Fu, P. M. Yavorsky, and I. Wender. 1972. Converting Organic Wastes to Oil. Agricultural Engineering, March. PP 17-20.

3. Appell, H. R., Y. C. Fu, S. Friedman, P. M. Yavorsky, and I. Wender. 1971. Converting Organic Wastes to Oil: A Replenishable Energy Source. RI-7560, Bureau of Mines, U.S. Department of the Interior. Pittsburgh Energy Research, Pittsburgh, Pennsylvania. 20 p.

4. Ashare, E., D. C. Augenstein, J. C. Young, R. J. Hossan, and G. L. Duret. 1978. Evaluation of Systems for Purification of Fuel Gas from Anaerobic Digestion. Engineering Report COO-299-44, Dynatech R/D Co., Cambridge, Massachusetts.

5. Beck, S. R. 1980. Economic Feasibility of Cattle Manure as a Chemical Feedstock. Proceedings, Fourth International Symposium on Livestock Wastes, Amarillo, Texas, April 15-17.

6. Beck, S. R., W. J. Huffman, B. L. Landeene, and J. E. Halligan. 1979. Pilot Plant Results for Partial Oxidation of Cattle Feedlot Manure. I&EC Process Design and Development, 18(2):328-332.

7. Burford, J. L., F. T. Varani, S. B. Don, and B. Pace. 1979. Energy Potential Through Bioconversion of Agricultural Wastes: Phase III. Final report to Four Corners Regional Commission, Grant No. 682-366-003, Bio-Gas of Colorado, Inc., Loveland, Colorado, January 14.

8. Egg, R. P. 1979. Batch Load Digestion of Dairy Manure. Presented at Extension Seminar on Methane Production from Livestock and Poultry Wastes, Texas Agricultural Extension Service, Texas A&M University, and Tarleton State University, Stephenville, Texas, May 23.

9. Engler, C. D., W. P. Walawender, and L. Fan. 1975. Synthesis gas from feedlot manure--conceptual design study and economic analysis. Environmental Science and Technology. 9(13):1152-1157.

10. Feldmann, H. F., K. D. Kiang, C. Y. Wen, and P. M. Yavorsky. 1973. Cattle Manure to Pipeline Gas: A Process Study. Mechanical Engineering, October, pp. 36-41.

11. Fischer, J. R., E. L. Iannoti, and D. M. Sievers. 1979. Biological and Chemical Fluctuations During Anaerobic Digestion of Swine Manure. (In press). USDA/Agricultural Research Service, Columbia, Missouri.

12. Fu, Y. C., E. G. Illig, and S. J. Metlin. 1974. Conversion of Manure to Oil by Catalytic Hydrotreating. Environmental Science and Technology, 8(8):737-740.

13. Fulton, E. L. 1979. Methane Generation from Poultry House Wastes. Final report, Tarleton State University, Stephenville, Texas, May 23.

14. Garner, W. and I. C. Smith. 1973. The Disposal of Cattle Feedlot Wastes by Pyrolysis. EPA-R2-73-096, U.S. Environmental Protection Agency, Washington, D.C.

15. Halligan, J. E. and R. M. Sweazy. 1972. Thermochemical Evaluation of Bovine Waste Conversion Processes. Presented at 72nd AICHE Meeting, St. Louis, Missouri.

16. Hamilton Standard. 1978. Monfort Dirt Lot Experiments: Status Report. Report No. COO-2952-17. U. S. Department of Energy, Washington, D. C.

17. Hashimoto, A. G., Y. R. Chen, and R. L. Prior. 1978. Thermophilic Anaerobic Fermentation of Beef Cattle Residue. In: Symposium Papers, Energy from Biomass and Wastes, Institute of Gas Technology, August 14-18, Washington, D. C.

18. Hashimoto, A. G., Y. R. Chen, V. H. Varel, and R. L. Prior. 1979a. Anaerobic Fermentation of Animal Manure. ASAE Paper No. 79-4066, American Society of Agricultural Engineers, St. Joseph, Michigan.

19. Hashimoto, A. G., Y. R. Chen, and R. L. Prior. 1979b. Methane and Protein Production from Animal Feedlot Wastes. Journal of Soil and Water Conservation, 34(1):16-19.

20. Hayes, T., W. J. Jewell, J. A. Chandler, S. Dell'orto, K. J. Fanfoni, A. P. Leuschner, and D. F. Sherman. 1979. Methane Generation from Small Scale Dairy Farms. Presented at Seminar on Biogas and Alcohol Production, The JG Press, Inc., Chicago, Illinois, October 25-26.

21. Henrich, T. 1979. Personal communication, Dual Fuel Systems, Inc., Montebello, California, November.

22. Huffman, W. J. 1978. Alternate Manure Recycling Systems for Energy Recovery. In: Methane Production from Livestock Manure (Proceedings of Great Plains Extension Seminar and Tour), Texas Agricultural Extension Service, Texas A&M University, College Station, Texas.

23. Huffman, W. J., J. E. Halligan, R. L. Peterson, and E. De la Garza. 1977. Ammonia Synthesis Gas and Petrochemicals from Feedlot Manure. Institute of Gas Technology, Symposium on Clean Fuels from Biomass. January 27, Orlando, Florida.

24. Kemp, M. D. 1978. The Potential of Biomass Conversion for the New Mexico Agribusinessmen. M.S. Thesis, Department of Mechanical Engineering, New Mexico State University, Las Cruces, New Mexico, August.

25. Kiang, K. D., H. F. Feldmann, and P. M. Yavorsky. 1973. Hydrogasification of cattle manure to pipeline gas. Presented at the 165th National Meeting, American Chemical Society, Dallas, Texas. April 8-13.

26. Knight, J. A., J. W. Tatom, M. D. Bowen, A. R. Colcord, and L. W. Elston. 1974. Pyrolytic Conversion of Agricultural Wastes to Fuels. ASAE Paper. No. 74-5017, presented at the 1974 Annual Meeting, American Society of Agricultural Engineers, St. Joseph, Michigan.

27. Kolb, R. 1980. Personal communication, Bradley Boiler Company, Inc., Twin Falls, Idaho, June 10.

28. Kreis, R. D. 1979. Recovery of By-Products from Animal Wastes--A Literature Review. EPA-600/2-79-142, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma. 50 p.

29. Ladd, K. L. 1979. Cotton Gin Trash Utilization Conference, Lubbock, Texas, October 15-16.

30. Ladd, K. L. 1980. Personal communication, Southwestern Public Service Company, Amarillo, Texas April 2.

31. Maciel, P. 1979. Status of the Imperial Valley Biogas Project. Presented at Seminar on Biogas and Alcohol Production, Chicago, Illinois, October 25-26.

32. Meckert, G. W., Jr. 1978. The Calorific Project. In: Methane Production from Livestock Manure, Proceedings of Great Plains Extension Seminar, Liberal, Kansas, (Texas Agricultural Extension Service), February 15.

33. Parker, H. 1980. Personal communication. The Engineering Societies Commission on Energy, Inc. (ESCOE). Washington, D. C., May 15.

34. Plunk, O. 1980. Personal communication, Southwestern Public Service Company, Amarillo, Texas, April 18.

35. Prokop, M. 1979. Personal communication, University of California, El Centro, California, October 29.

36. Sweeten, J. M. 1979. Prospects for Methane Production at Cattle Feedlots. High Plains Extension Seminar on Feedlot Manure for Fertilizer and Fuel, Dimmitt, Texas, November 28.

37. Sweeten, J. M. and A. Higgins. 1980. Results of Feedlot Manure Characterization Study at Swisher County Cattle Company. Special Report, Texas Agricultural Extension Service, The Texas A&M University System, College Station, Texas.

38. Sweeten, J. M., D. L. Reddell, and B. R. Stewart. 1974. Feedlot Manure as an Energy Source. Paper presented at the 1974 Texas Section Meeting, American Society of Agricultural Engineers, Abilene, Texas, October 4-5.

39. Texas Railroad Commission. 1980. Motor Freight Commodity Tariff No. 8-I, Railroad Commission of Texas, February 1.

40. Walawender, W. P., L. T. Fan, C. R. Engler, and L. E. Erickson. 1973a. Feedlot Manure and Other Agricultural Wastes as Future Material and Energy Resources: II. Process descriptions. Contribution No. 30, Department of Chemical Engineering, Kansas Agricultural Experiment Station, Manhattan, Kansas. 30 p.

41. Walawender, W. P., L. T. Fan, C. R. Engler, and L. E. Erickson. 1973b. Feedlot Manure and Other Agricultural Wastes as Future Material and Energy Resources: III. Economic evaluation. Contribution No. 33, Department of Chemical Engineering, Kansas Agricultural Experiment Station, Manhattan, Kansas. 23 p.

42. Walmet, G. 1979. Biogas Purification with Perm Selective Membranes. Presented at Seminar on Biogas and Alcohol Production, The JG Press, Inc., Chicago, Illinois, October 25-26.

43. Yager, W. E. 1980. Personal communication, Swindell-Dressler Energy Supply Company, Amarillo, Texas, April 18.

44. Young, H. D., J. E. Halligan, and H. W. Parker. 1973. The Chemical Conversion of Bovine Waste. Presented at first annual Air Pollution Control Symposium, Texas A&M University, College Station, Texas.

45. Zinn, R. A., F. N. Owens, and R. P. Lake. 1979. Sludge Evaluation. 1979 Animal Science Research Report, Oklahoma Agricultural Experiment Station, Stillwater, Oklahoma, pp. 35-36.