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FEASIBILITY FOR ENERGY RECOVERY FROM CEREAL CROP RESIDUES

by

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the University of Manitoba in partial fulfillment of the requirements
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ABSTRACT

Feasibility for Energy Recovery from Cereal Crop Residues

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Solid waste management and the depletion of fossil fuel reserves are two critical and unrelated problems requiring resolution. An approach to the solution of these two problems by conversion of solid organic wastes into useful forms of energy was investigated. Canada is fortunate to possess rich natural resources including fossil fuels, however, there is a concern expressed through the wide-spread "energy crisis" that shortages will be encountered in the immediate future. Canada produces about 99.0×10^9 lb (44.9×10^9 kg) of cereal crop residues annually which should not be overlooked as a potential energy source. Much of this residue is considered as waste material which creates problems of disposal and affects on the environment. This quality of residues has a potential energy equivalent to about 593.4×10^{12} Btu (149.5×10^{12} kcal).

Oat straw was chosen as a representative cereal crop residue for investigating the feasibility of energy recovery by pyrolysis and anaerobic fermentation. A significant volume of gas production was achieved with both systems. Gas production from the pyrolysis process was 1.43 cu ft/lb (0.09 litre/gm) of straw and 1.78 cu ft/lb (0.11 litre/gm) of straw at the corresponding temperature ranges of 65 to 600°F (18 to 316°C) and 65 to 700°F (18 to 371°C). The gas contained from 25 to 30% CH₄, and 32 to 48% CO₂. The gas production through anaerobic digestion at a temperature of 95°F (35°C) was about 6.57 cu ft/lb (0.41 litre/gm) of dry matter for the batch feeding system and about 6.01 cu ft/lb

(0.38 litre/gm) of dry matter for the continuous feeding system. The composition of gas was approximately 52 to 56% CH₄, and 44 to 48% CO₂.

Problems of materials handling of straw involving collection, concentration and transportation for the delivery of large quantity volumes to supply large pyrolysis or anaerobic processing plants must be solved. Straw should be delivered in a form that will facilitate pyrolysis or anaerobic energy production processes. The economics of pyrolysis and anaerobic digestion for energy recovery from crop residues has been unfavourable to date. However, the extraction of useful energy from cereal crop residues is technically feasible and merits serious investigation.

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LIST OF SYMBOLS

abs	=	absolute
ave	=	average
bu	=	bushel
Btu	=	British thermal unit
°C	=	degree Celsius
cal	=	calorie
Can \$	=	Canadian dollar
cm	=	centimeter
cu ft	=	cubic foot
cu m	=	cubic meter
°F	=	degree Fahrenheit
ft	=	foot
gal	=	gallon
gm	=	gram
hp	=	horse power
hr	=	hour
kcal	=	kilocalorie
kg	=	kilogram
km	=	kilometer
kwh	=	kilowatt hour
lb	=	pound
m	=	meter
min	=	minute
mg	=	milligram
ml	=	millilitre
mton	=	metric ton

ppm = parts per million
psi = pounds per square inch
psia = pounds per square inch absolute
Ref = reference
SCFM = standard cubic feet per minute
sec = second
sq cm = square centimeter
temp = temperature
U.S. \$ = United States dollar
vol = volume
VS = volatile solid

CHAPTER I

INTRODUCTION

1.1 General

Energy is necessary to provide power for all forms of work. Not only our body, but also our life-support systems, agriculture and industry, require energy. If energy is withdrawn from agriculture and industry, our life-support systems cease to function (33, 54). Energy consumption can be used as a measure of the progress of civilization which can be applied to industry and the economy in general. In any society, as the development of civilization progresses, energy consumption increases. Conversely, if the society does not have enough energy, civilization as we have known it will be halted (64). David Cass-Beggs (8), in an address to an international biomass energy conference, stated that "energy use and civilization are a reaction that goes both ways".

Scientific American (14) shows that the annual growth in energy demand per capita in the United States is at the rate of about one percent while in India the rate of increase is about one third of the United States rate. Data presented for 1970 show that United States energy consumption was about 220 kwh/day/capita while in India it was about nine kwh/day/capita. McGinnis (44) estimated that annual energy consumption in Canada in 1970 was about $4,939.5 \times 10^{12}$ Btu or approximately 184 kwh/day/capita.

An improved standard of living demands increased consumption which is a combination of two factors; the energy used per capita and the number of people. A pressing problem facing society is that the relationship of man and energy may become a critical problem in the near future. Then, "the question nowadays is not how we shall live,

but indeed if we are going to live at all for very much longer" (Harney, Disch, 1971, p. xvii) (64). The need for solving the energy problem is apparent (8, 61, 64).

1.2 The Problems

1.2.1 The Coming Shortage of Some Fossil Fuels

The energy crisis has become a dominant issue during the past few years (33). The current world energy shortage has stimulated a search for alternative sources of energy, since fossil fuel reserves are being depleted rapidly (14). It is not an objective of this thesis to present statistics of the world's energy situation. It is not a matter of how long the primary energy sources will last, but rather it is a matter of fact that reserves have specific quantity limits, and that energy fuels can not be recycled. "When they are gone, they are gone" (72). The energy crisis has become a reality and the question arises as to what other sources of energy can be tapped to supply the requirements after the fossil fuels are gone (14, 15, 33, 44).

Various alternative energy sources including solar, tidal, geothermal and nuclear will be investigated thoroughly in the immediate future. A further source may be energy from agricultural production or "biomass energy" which is a renewable resource that offers the possibility of providing an alternative energy source (14, 43).

1.2.2 Increase in Solid Wastes and Associated Problems

It is understood that solid wastes refer to the wastes arising from household, industrial and agricultural sources. In the past, solid wastes were commonly disposed by means of open burning or open dumping.

At present, the situation has changed and solid waste disposal is becoming a problem of considerable magnitude both with respect to disposal methods and to economic constraints. This problem arises from the increase in total quantity of waste produced through population increase and per capita increase in waste produced because of changes in the standard of living (53, 61). Riddle (53) estimated that total solid waste produced in Canada to be about 160 million pounds (73 million kilograms) per day or eight pounds (3.6 kilograms) per capita per day, of which 100 million pounds (45 million kilograms) is from households while the remaining arises from industrial and agricultural sources.

Wastes from agricultural sources are primarily organic. Two kinds of agricultural wastes which are considered here as potential sources of energy are agricultural plant wastes (crop residue) and animal wastes (manure) (33, 70). Both sources have been increasing the total quantity of wastes. The increase in animal waste has resulted from the increase of animal feedlots while the increase in crop residue has resulted from increased acreage under production combined with greater efficiency in unit productivity, e.g., irrigation, fertilization, and the influence of mechanization, etc. (12, 70).

In past years, agricultural wastes presented no problem, since it was disposed of on the land as a fertilizer. Today, because of the volume of waste generated in confinement areas, disposal on land is a problem and an overall management scheme must be considered for waste handling (46). We are now considering waste not so much as material to be eliminated, but rather as a resource (61). Once we begin to use it, it will no longer be called waste (70).

Downing (12) has calculated that the ratio of energy output to

energy input is very favorable for agricultural production. He concluded that "the utilization of either net crop residue or animal wastes as a fuel source could produce more energy than required for all agriculture production requirements". Therefore, the present problem is not only a matter of disposal technique, but it includes processing for recovery and utilization of useful components in these agricultural wastes.

1.3 Objective

The objective of this thesis is to evaluate the technical and economic feasibility of recovering energy from cereal crop residues.

1.4 Conceptual Approach

Organic material or agricultural waste may be converted into a useful energy by direct combustion for thermal energy or biological or chemical processes for storable chemical energy. The choice of conversion method depends on the physical nature of material, particularly the water content (47). The first step toward meeting the objective was to complete a literature review. In addition, the development of small-scale experiments on pyrolysis and anaerobic processes is included. The major concentration in this thesis is directed to pyrolysis.

Anaerobic digestion studies have been undertaken by many institutions. Few of these institutions have set up experiments to see if anaerobic digestion could be applied to crop residues. Pyrolysis was chosen for investigation since this process has been successfully used to recover energy from organic material in times and places of restricted energy supply. For example, gas producer plants making use of coal were used for road transport in Europe during World War II. Pyrolysis may prove viable as a process for energy recovery from straw.

CHAPTER II

QUANTITY OF RESIDUE AVAILABLE

2.1 General

The discussion in this thesis is related to residues from cereal crops only. Several definitions follow:

Cereal: "A cereal may be defined as any grass grown for its edible grain. The term may refer either to the plant as a whole or to the grain itself" (30).

Grain: "Grain is a collective term for the fruit of cereals" (30).

The principle cereals refer to wheat, corn, rice, barley, oats, rye, sorghum and millet (29). However, the six great cereals of the world are considered to be wheat rye, barley, corn, oats and rice (30). The discussion in this thesis will deal with these six cereals only.

2.2 Grain-straw Ratio

The quantity of crop residue can be computed as a function of crop production and may be determined by the use of the grain to straw ratio. For cereals, Kipps (30) explained that the ratio of grain to straw is not constant and varies with such factors as the variety, thickness of planting, and productivity of the soil. However, he concluded that the ratio of grain to straw may be given as follows:

Barley produces 1 pound of grain to 1 pound of straw (1:1).

Wheat produces 1 pound of grain to 1.5 pounds of straw (1:1.5).

Oats produces 1 pound of grain to 2 pounds of straw (1:2).

Rye produces 1 pound of grain to 2 pounds of straw (1:2).

Corn produces 1 pound of grain to 1 pound of stover (1:1).

For rice, the ratio of grain to straw was given in a report from the International Rice Research Institute, Los Banos, Laguna, The Phillippines. Chandler (9) stated that the grain-straw ratio was affected by a number of factors such as nitrogen applications, percent of sunshine, and varieties of rice. In general, the traditional rice plant of the tropics has a grain-straw ratio between 0.3 and 0.6, while the modern rice plant with short stem and erect leaves has a ratio between 0.9 and 1.3. In the first case, the mean value of grain-straw ratio for selected varieties is 0.56 (or 1:1.8). This figure will be used for the discussion throughout this thesis, since it is applicable to the varieties of rice grown in Thailand (see Table 2.9). Therefore,

Rice produces 1 pound of grain to 1.8 pounds of straw (1:1.8).

2.3 Weights per Bushel for Conversion

It is necessary to use conversion factors in estimating quantities of crop residues available. Weights per bushel for the principle cereals as taken from Grain Crops, published by the Commonwealth Secretariat (20), are given in Table 2.1.

2.4 Limits for the Study

The scope of study in this thesis was defined by the criteria following:

2.4.1 Cereal crops were to include wheat, barley, oats, rye, grain corn, and rice.

2.4.2 The acreage and production of cereal crops, except rice were limited to the total acreage and production in Canada, Manitoba and Crop District No. 3 in Manitoba. The agricultural areas of Manitoba and Crop District No. 3 are shown in Figure 2.1.

2.4.3 Statistics used for crop residue estimates are average grain production values for the year 1968, 1969, and 1970 in Canada, Manitoba and Crop District No. 3.

2.4.4 The acreage and production of rice was taken for Thailand, since rice was almost negligible in Canadian production statistics, for the years noted in section 2.4.3 and since Thailand is the homeland of the author.

2.5 Production

The quantity of cereal crop residue is a function of production and is estimated by using the ratio of grain to straw. Table 2.2 contains the average yield and production in Canada, Manitoba and Crop District No. 3. Statistics for Canada were taken from the 1971 and 1972 Canada Yearbooks (68, 69) and for Manitoba from the 1968, 1969 and 1970 Yearbooks of Manitoba Agriculture (78). The figures for rice were taken from a record of Thailand (3) compiled by the Rice Department for 1968 and the Agricultural Extension Department for 1969 and 1970. A summary of the acreage, yields and production of cereal crops in Canada and Thailand is contained in Table 2.4.

Date relating to rye and grain corn in Manitoba were not given for crop districts. Therefore, production quantities for these crops were not considered for Crop District No. 3. Referring to rye, the 1970 Yearbook of Manitoba Agriculture (78) stated that "seventy-eight percent of the total acreage was planted in the western half of the province and about eighteen percent in Crop District No. 3". There was no planted acreage in the year 1968 and 1969. There are no details given for grain corn, since the total planted area in Manitoba was small. Therefore, rye and grain corn production in Crop District No. 3 was considered to be

negligible and was not used in estimating the residues available.

The acreage, yield and production of rice in Thailand are given in Table 2.3.

2.6 Estimated Quantity of Residues Available

The estimated quantities of residues available in Canada, Manitoba and Crop District No. 3 were determined by using grain to straw ratios and are shown in Tables 2.5, 2.6 and 2.7 respectively. A summary of the amount of residue for each cereal crop is shown in Table 2.8. An estimate of the total quantity of residues available in Canada follows:

	<u>Estimated Quantity of Residue</u>	
	<u>(10⁹ lb)</u>	<u>(10⁹ kg)</u>
Canada	99.0	44.9
Manitoba	12.3	5.6
Crop District No. 3	1.9	0.9

The total cereal crop residue in Manitoba is about 12.4% of that in Canada, while the residue in Crop District No. 3 is about 15.4% of that in Manitoba.

2.7 Discussion and Conclusions

The quantity of residues shown in the proceeding section is the potential quantity of residues derived from the average total production in Canada and Manitoba for 1968 to 1970. However, not all of the potential quantity of residues may be collected for converting into useful energy. Downing (12) estimated that "half of the residue is returned to the soil for the maintenance of the humus content and that straw is used for bedding at the rate of one-half ton/cattle unit housed".

Thus the net quantity of residues available will probably be about half of the potential quantity of residues. Therefore, in the determination of energy available, this factor should be taken into consideration.

TABLE 2.1

Weights per Bushel for Principle Cereals¹

Cereals	lb/bu
Wheat	60
Barley	48
Oats	32
Rye	56
Corn	56
Paddy (rough rice)	45

¹Grain Crops, London: The Commonwealth Secretariat, 1972, p. v.

TABLE 2.2
Acreage, Yields, and Production of Cereal Crops in Canada¹, Manitoba²,
and Crop District No. 3 of Manitoba² for the Period 1968-1970

No.	Cereal	Area ³ in 1000 Acres			Yield in bushel/acre			Production ³ in 1000 bushels		
		Canada	Manitoba	District 3	Canada	Manitoba	District 3	Canada	Manitoba	District 3
1.	Wheat									
	1968	29,422	3,400	595	22.1	26.8	27.3	649,844	91,000	16,216
	1969	24,968	2,500	395	27.4	25.6	18.5	684,276	64,000	7,309
	1970	12,484	1,400	297	26.6	21.8	19.4	331,519	30,500	5,774
	Average	22,291	2,433	429	25.4	24.7	21.7	555,213	61,833	9,766
2.	Oats									
	1968	7,556	1,580	320	48.0	51.3	55.1	362,516	81,000	17,627
	1969	7,655	1,530	291	48.5	45.1	38.6	371,387	69,000	11,238
	1970	7,149	1,260	203	51.5	42.1	39.1	367,850	53,000	7,933
	Average	7,453	1,457	271	49.3	46.2	44.3	367,251	67,667	12,266
3.	Barley									
	1968	8,836	1,170	211	36.8	36.8	35.7	325,373	43,000	7,542
	1969	9,535	1,200	217	39.7	35.0	25.9	378,383	42,000	5,625
	1970	10,043	1,500	275	41.4	34.0	29.8	415,704	51,000	8,191
	Average	9,471	1,290	234	39.3	35.3	30.5	373,153	45,333	7,119
4.	Rye									
	1968	679	120	*	19.2	20.8	*	13,019	2,500	*
	1969	927	183	*	17.8	18.3	**	16,493	3,358	*
	1970	1,015	194	*	22.1	21.5	*	22,427	4,177	*
	Average	874	166	*	19.7	20.2	*	17,313	3,345	*
5.	Grain corn									
	1968	958	2.5	*	84.7	40.0	*	81,168	100	*
	1969	978	3.0	*	75.1	33.3	*	73,426	100	*
	1970	1,197	3.5	*	84.3	50.0	*	100,925	175	*
	Average	1,044	3.0	*	81.4	41.1	*	85,173	125	*

¹1971 and 1972 Canada Yearbooks, Statistics Canada

²1968, 1969 and 1970 Yearbooks of Manitoba Agriculture

³Rounded figures are used

*No data available

TABLE 2.3

Acreage, Yields and Production of Cereal Crops in Thailand¹
for the period 1968-1970

No.	Cereal	Area ² in (1000)		Yield			Production ² in (1000)		
		Rais	Acres	kg/rai	lb/acre	bu/acre	kg	lb	bu
1.	Rice								
	1968	39,602	15,841	261	1,438.1	32.2	10,336,122	22,780,942	506,912
	1969	45,285	18,114	295	1,625.5	36.1	13,359,075	29,444,307	653,915
	1970	44,569	17,828	300	1,653.0	36.7	13,370,700	29,469,684	654,288
	Average	43,152	17,261	285	1,572.2	34.9	12,355,299	27,231,644	605,038

¹ Rice Department for 1968² Agricultural Extension Department for 1969, 1970

Rounded figures are used

1 Acre = 2.5 Rais

1 kg = 2.204 lb

1 bu (of paddy) = 45 lb

TABLE 2.4

A Summary of Acreage, Yields, and Production of Cereal Crops in Canada and Thailand

No.	Cereal	Area in 1000 acres			Yield in bushel/acre			Production in 1000 bushels		
		Canada	Manitoba	District 3	Canada	Manitoba	District 3	Canada	Manitoba	District 3
1.	Wheat	22,291	2,433	429	25.4	24.7	21.7	555,213	61,833	9,766
2.	Oats	7,453	1,457	271	49.3	46.2	44.3	367,251	67,667	12,266
3.	Barley	9,471	1,290	234	39.3	35.3	30.5	375,153	45,533	7,119
4.	Rye	874	166	*	19.7	20.2	*	17,313	3,345	*
5.	Grain corn	1,044	3	*	81.4	41.1	*	85,173	125	*
	Thailand		-	-	Thailand	-	-	Thailand	-	-
6.	Rice	17,261	-	-	34.9	-	-	605,083	-	-

* not available

TABLE 2.5

The Quantity of Cereal Crop Residues Available in Canada and Thailand

No.	Description	Unit	Cereal Crops					
			Wheat ¹	Oats ¹	Barley ¹	Rye ¹	Grain Corn ¹	Rice ²
1.	Acreage	10 ³ acres	22,291	7,453	9,471	874	1,044	17,261
2.	Yield (by volume)	bu/acre	25.4	49.3	39.3	19.7	81.4	34.9
3.	Production	10 ³ bu	555,213	367,251	373,153	17,313	85,173	605,038
4.	Weight/bushel	lb/bu	60	32	48	56	56	45
5.	Grain: straw ratio	lb/lb	1:1.5	1:2	1:1	1:2	1:1	1:1.8
6.	Yield (by weight)	lb/acre	1,524.0	1,577.6	1,886.4	1,103.2	4,558.4	1,572.2*
7.	Straw per unit area	lb/acre	2,286.0	3,155.2	1,866.4	2,206.4	4,558.4	2,830.0
8.	Total amount of straw	10 ⁶ lb	50,957.2	23,515.7	17,866.1	1,928.4	4,759.0	48,848.6

¹Cereal crops in Canada (excluding Newfoundland)²Cereal crops in Thailand

* Figure from Table 2.3

TABLE 2.6

The Quantity of Cereal Crop Residues Available in Manitoba

No.	Description	Unit	Cereal Crops					
			Wheat	Oats	Barley	Rye	Grain Corn	Rice
1.	Acreage	10 ³ acres	2,433	1,457	1,290	166	3.0	*
2.	Yield (by volume)	bu/acre	24.7	46.2	35.3	20.2	41.1	*
3.	Production	10 ³ bu	61,833	67,667	45,333	3,345	125	*
4.	Weight/bushel	lb/bu	60	32	48	56	56	*
5.	Grain: straw ratio	lb/lb	1:1.5	1:2	1:1	1:2	1:1	*
6.	Yield (by weight)	lb/acre	1,482.0	1,478.4	1,694.4	1,131.2	2,301.6	*
7.	Straw per unit area	lb/acre	2,223.0	2,956.8	1,694.4	2,262.4	2,301.6	*
8.	Total amount of straw	10 ⁶ lb	5,408.6	4,308.1	2,185.8	375.6	6.9	*

* not available

TABLE 2.7

The Quantity of Cereal Crop Residues Available in Crop District No. 3 of Manitoba

No.	Description	Unit	Cereal Crops					
			Wheat	Oats	Barley	Rye	Grain Corn	Rice
1.	Acreage	10 ³ acres	429	271	234	*	*	*
2.	Yield (by volume)	bu/acre	21.7	44.3	30.5	*	*	*
3.	Production	10 ³ bu	9,766	12,266	7,119	*	*	*
4.	Weight/bushel	lb/bu	60	32	48	*	*	*
5.	Grain: straw ratio	lb/lb	1:1.5	1:2	1:1	*	*	*
6.	Yield by weight	lb/acre	1,302.0	1,417.6	1,464.0	*	*	*
7.	Straw per unit area	lb/acre	1,953.0	2,835.2	1,464.0	*	*	*
8.	Total amount of straw	10 ⁶ lb	837.8	768.3	342.6	*	*	*

* not available

TABLE 2.8
A Summary of the Total Quantity of Cereal Crop Residues Available

No.	Cereal	Unit	Location		
			Canada	Manitoba	District 3
1.	Wheat	10 ⁶ lb	50,957.2	5,408.6	837.8
2.	Oats	"	23,515.7	4,308.1	768.3
3.	Barley	"	17,866.1	2,185.8	342.6
4.	Rye	"	1,928.4	375.6	*
5.	Grain corn	"	4,759.0	6.9	*
	Total	"	<u>99,026.4</u>	<u>12,285.0</u>	<u>1,948.7</u>
			<u>Thailand</u>	-	-
6.	Rice	"	48,848.6	-	-

* not available

TABLE 2.9
Grain-Straw Ratio for Selected Rice Varieties¹

Class	Variety	Grain-Straw Ratio
Highly nitrogen responsive	IR 8	1.15
	Chianung 242	1.14
	Taichung Native 1	1.20
	Tainan 3	1.23
	IR 5	0.95
	<u>Mean</u>	1.13
Low or negatively responsive to nitrogen	Hung	0.60
	Peta	0.60
	Nang Mong S ₄ *	0.49
	Puang Nahk 16*	0.40
	H-4	0.58
	Sigadis	0.69
	<u>Mean</u>	0.56

¹Robert F. Chandler, Jr., International Rice Research Institute, Los Baños, Laguna, The Philippines.

*Varieties of rice in Thailand.

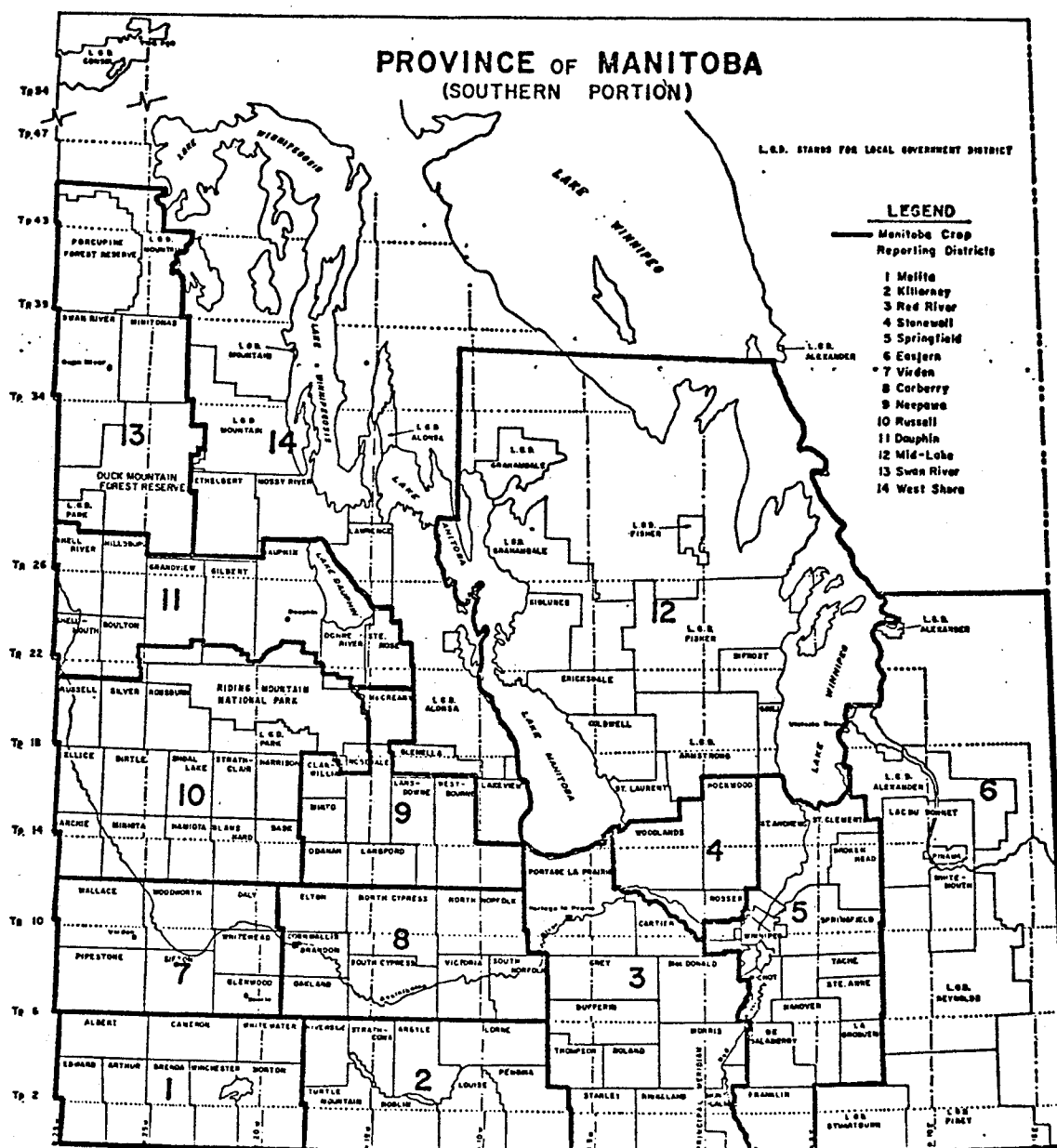


FIGURE 2.1 The Agricultural Areas of Manitoba
and Crop District No. 3 (Ref. 78)

CHAPTER III

QUANTITY OF ENERGY AVAILABLE

3.1 General

Agricultural products represent an immense source of energy. In addition to the energy contained in the primary product of food, feed and fibre, non-product output such as crop residues contains energy which may be converted to heat or chemical energy by direct burning or fermenting. The discussion in this chapter deals with the quantity of energy recoverable from straw. A knowledge of some technical terms involved will facilitate an understanding of the approach to the determination of the quantity of energy available.

3.1.1 Definition of Terms

Thermal value: This term is also known as calorific or heat value. As defined by Johnson (27), "The thermal value of a fuel is the amount of heat generated as a result of its complex combustion". This value is generally expressed in British thermal units (Btu) per pound, or calories per gram. There are two limits of heat value, i.e., higher and lower heat values.

Higher heat value: The value indicated by any type of a fuel calorimeter (60).

Lower heat value: This is known as "net" or "available" heat value. It is used in the case of fuel containing hydrogen, and this includes practically all fuels in commercial use. The lower heat value may also be defined as the net heat liberated per unit weight of fuel after the heat necessary to vaporize the steam formed from the hydrogen, as well as that from the fuel, has been deducted (60). It is related

to the higher heat value as follows (27):

Lower heat value = higher heat value - wr ; (compatible units)

where:

w = weight of water produced per unit weight of fuel

r = latent heat recovered in the condensation of the water vapor formed in the combustion of hydrogen.

The value of r varies with percentage of hydrogen in the fuel, the moisture in the air and the temperature to which the products of combustion are cooled in the calorimeter.

British thermal unit: (Btu) "The amount of heat required to raise the temperature of one pound of water one degree Fahrenheit" (27).

Calorie (gram-calorie): Defined as the quantity of heat required to raise the temperature of one gram of water one degree Celsius.

3.2 Conversion Factors

The conversion factors given in Tables 3.1 and 3.2 will be useful to the discussion in this chapter.

Table 3.1

Conversion of Thermal Units to Energy and Work Equivalent¹

Btu	kcal ²	ft-lb	hp-hr	kwh
1	0.252	778.2	0.0003930	0.0002930
3.968	1	3,088.0	0.001560	0.001163
0.001285	0.0003238	1	0.00000050505	0.0000003765
2,544	641.1	1.98×10^6	1	0.7455
3,413	840.0	2.656×10^6	1.341	1

¹Lionel S. Marks, Mechanical Engineers Handbook, 4th ed. New York: McGraw-Hill Book Company, Inc., 1941, p. 79.

²1 kcal = 1,000 calories

TABLE 3.2

Conversion Factors for Energy, Work and Heat¹

Btu to foot-pounds	778.2	Foot pounds to Btu	0.001285
Btu to calories	252	Calories to Btu	0.003968
Btu to horsepower-hours	0.000393	Horsepower-hours to Btu	2,544
Btu to kilowatt-hours	0.000293	Kilowatt-hours to Btu	3,413

¹Allen J. Johnson and George H. Auth, Fuels and Combustion Handbook, 1st ed. New York: McGraw-Hill Book Company, Inc., 1951, p. 364.

3.3 Heat Value of Straw

Straw from different crops as well as different fields of the same crop have different heat value. It is given by Marks (42) that "straw, from which grain has been threshed, has a higher heat value (hhv) of 5,000 to 6,500 Btu/lb depending upon its degree of dryness". However, McGinnis (44) mentioned that "The straw from all crops has approximately equal value with as much variation between fields of the same crop as between different crops. A value of 5,000 to 6,500 Btu/lb of straw has been established with an average of about 6,000 Btu/lb". Therefore, the value of 6,000 Btu/lb (3,330 kcal/kg) will be used throughout the discussion in this thesis.

3.4 Estimated Quantity of Energy Available

The quantity of energy available in Canada, Manitoba and Crop District No. 3 in Manitoba is shown in Tables 3.3, 3.4 and 3.5 respectively. The total estimate of energy available is summarized as follows:

TABLE 3.3
The Quantity of Energy Available from Straw in Canada and Thailand

No.	Description	Unit	Cereal Crops					
			Wheat ¹	Oats ¹	Barley ¹	Rye ¹	Grain Corn ¹	Rice ²
1.	Acreage ³	10 ³ acres	22,291	7,453	9,471	874	1,044	17,261
2.	Amount of straw per unit area ³	lb/acre	2,286.0	3,155.2	1,886.4	2,206.4	4,558.4	2,830.0
3.	Heating value of straw ⁴	Btu/lb	6,000	6,000	6,000	6,000	6,000	6,000
4.	Amount of energy per unit area	10 ⁶ Btu/acre	13.7	18.9	11.3	13.2	27.4	17.0
5.	Total amount of energy	10 ¹² Btu	305.4	140.9	107.0	11.5	28.6	293.4

¹Cereal crops in Canada

²Cereal crops in Thailand

³Figures from Table 2.5

⁴Figures from McGinnis (44)

TABLE 3.4

The Quantity of Energy Available from Straw in Manitoba

No.	Description	Unit	Cereal Crops					
			Wheat	Oats	Barley	Rye	Grain Corn	Rice
1.	Acreage ¹	10 ³ acres	2,433	1,457	1,290	166	3.0	*
2.	Amount of straw per unit area ¹	lb/acre	2,223.0	2,956.8	1,694.4	2,262.4	2,301.6	*
3.	Heating value of straw ²	Btu/lb	6,000	6,000	6,000	6,000	6,000	*
4.	Amount of energy per unit area	10 ⁶ Btu/acre	13.3	17.7	10.2	13.6	13.8	*
5.	Total amount of energy	10 ¹² Btu	32.4	25.8	13.2	2.3	0.04	*

*not available

¹Figures from Table 2.6²Figures from McGinnis (44)

TABLE 3.5

The Quantity of Energy Available from Straw
in Crop District No. 3 of Manitoba

No.	Description	Unit	Cereal Crops					
			Wheat	Oats	Barley	Rye	Grain Corn	Rice
1.	Acreage ¹	10 ³ acres	429	271	234	*	*	*
2.	Amount of straw per unit area ¹	lb/acre	1,953.0	2,835.2	1,464.0	*	*	*
3.	Heating value of straw ²	Btu/lb	6,000	6,000	6,000	*	*	*
4.	Amount of energy per unit area	10 ⁶ Btu/acre	11.7	17.0	8.8	*	*	*
5.	Total amount of energy	10 ¹² Btu	5.0	4.6	2.1	*	*	*

*data not available

¹Figures from Table 2.7

²Figures from McGinnis (44)

	<u>Energy Available from Straw</u>	
	<u>(10^{12} Btu)</u>	<u>(10^{12} kcal)</u>
Canada	593.4	149.5
Thailand	293.4	73.9
Manitoba	73.7	18.6
Crop District No. 3	11.7	2.9

From the above values, it can be shown that the energy available from straw in Crop District No. 3 is about 15.9% of that in Manitoba while Manitoba's potential recovery represents about 12.4% of the energy available from straw in Canada.

3.5 Discussion and Conclusions

Values in section 3.4 show that the quantity of energy available from straw is of considerable magnitude. In comparison with the total 1970 Canadian energy consumption of $4,939.5 \times 10^{12}$ Btu ($1,244.8 \times 10^{12}$ kcal) (44) (see also Table 3.7) from various sources, the energy available from straw in Canada is about 12.0% of the total energy consumption in 1970 or almost one-fourth (23.7%) of the total crude petroleum consumption.

Based on the total 1970 Canadian energy consumption of $4,939.5 \times 10^{12}$ Btu ($1,244.8 \times 10^{12}$ kcal) and the total population of 21,568,311 for 1971 census year, the rate of energy consumption per capita per year would be about 229×10^6 Btu (or 0.627×10^6 Btu/capita/day, or 184 kwh/capita/day).

For the 1971 census year, the population of Manitoba was 988,247.. Therefore, the total annual energy consumption in Manitoba would be about 219.4×10^{12} Btu (55.3×10^{12} kcal). From the value determined in section 3.4, the quantity of energy available from straw (73.7×10^{12} Btu

or 18.6×10^{12} kcal) would provide about 33.6% of the total annual consumption in this province. Similarly, the quantity of energy available from straw in Crop District No. 3 would provide about 5.3% of the total annual consumption of Manitoba. The values are shown in Table 3.6.

TABLE 3.6

Percentage of Energy Available from Straw to Energy Consumed

Location	Energy available from straw (10^{12} Btu) (1)	Annual energy consumption, 1970 (10^{12} Btu) (2)	Percentage of (1) to (2) %
Canada	593.4	4,939.5	12.0
Thailand	293.4	*	*
Manitoba	73.7	219.4	33.6
Crop District 3	11.7	*	*

* data not available

The above values were computed from the total available quantity of straw. Should only 50 percent of the straw available be collected as contained in section 2.7 of Chapter II, then, the energy available from straw and the percentage in Table 3.6 will be reduced accordingly by 50 percent.

TABLE 3.7

Annual Canadian Consumption from Various Energy Sources¹

Energy Source	Annual Heat Consumption (10 ¹²) Btu
Natural gas	918.5
Hydroelectric	526.0
Thermoelectric	162.0
Coal	833.0
Crude petroleum	2,500.0
TOTAL	4,939.5

¹Robert C. McGinnis, "Potential Biomass Crops." Paper presented at the International Biomass Energy Conference Winnipeg, Canada, May 13-15, 1973, p. 9.

CHAPTER IV

METHODS OF CONVERSION OF RESIDUES TO USEFUL ENERGY

4.1 General

The depletion of fossil fuel reserves and the disposal of wastes represent two real problems facing society. Volumes and characteristics of wastes such as animal manure and crop residues are such that disposal or degradation are difficult. The increasing demand for energy has now exceeded the domestic production of some petroleum fuels, e.g., oil and natural gas in the United States (70). The use of other fossil fuel resources including coal and oil shale requires new technology development so that energy fuels produced will meet environmental and economic constraints. The needs of a modern energy oriented society necessitate the development of additional sources of clean energy. Alternate potential energy sources include solar, tidal, geothermal, nuclear, wind and biomass energy (14, 47, 75). These resources are being considered as possible alternatives for fossil fuels whose known reserves have diminished to critical levels. Discussion in this chapter deals only with the energy from agricultural wastes, or biomass energy, particularly from crop residues.

Crop residues as noted in Chapters II and III may be considered as a partial alternative source for energy fuels. However, the real problems are how to transform the energy into a satisfactory form for use with good efficiency of conversion and at cost competitive with present types of energy (12). Downing (12) stated that the present efficiency for the conversion of animal waste to methane gas is less than 50% and is about 30% for converting wheat into alcohol. This problem

has to be considered in making an economic analysis of energy conversion processes.

Technically, the problems related to converting organic waste materials to useful energy are due to their variable composition and degree of degradation. In general, organic wastes can be converted directly into thermal energy by combustion or can be converted to storable chemical energy by a number of biological or chemical processes (47).

The choice of conversion method is frequently dictated by the physical and chemical nature of the material. For example, waste materials having a very high water content would be more profitably converted into a storable fuel by a biological process that operates in an aqueous medium, e.g. an anaerobic or an aerobic process. In other cases, where relatively dry waste materials are resistant to biodegradation, the direct combustion to heat energy or conversion to concentrated fuels by a chemical process, such as pyrolysis, would be comparatively feasible (47).

Figure 4.1 displays methods available for the conversion of residues to useful energy

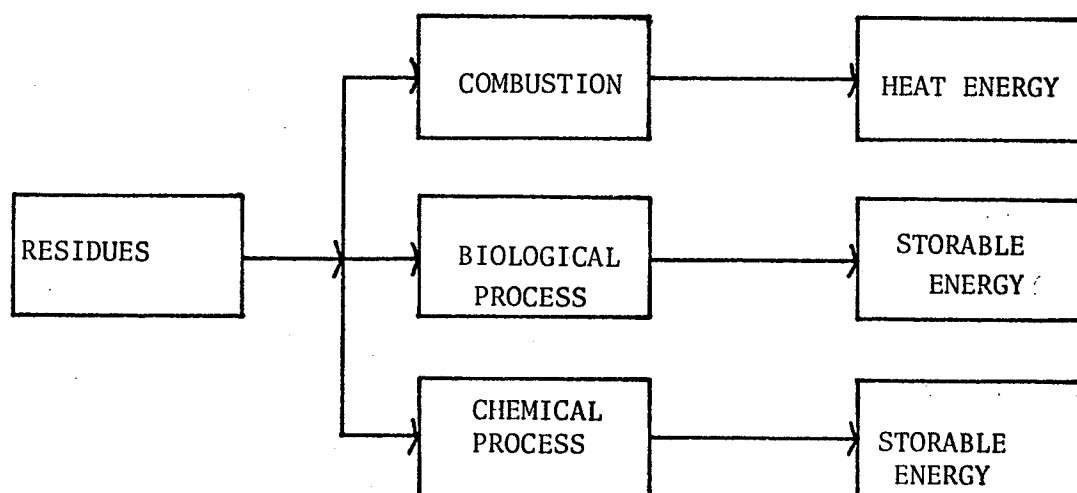


FIGURE 4.1 Methods of Conversion of Residues into Useful Energy

The discussion of conversion methods in this chapter will be on pyrolysis and anaerobic digestion with greatest emphasis directed to pyrolysis.

4.2 Pyrolysis

4.2.1 Definition of Terms

Pyrolysis: The simplest definition found in the literature states that "Pyrolysis is simply the heating of a material to a high temperature in the absence of air - the method for producing coke from coal or charcoal from wood" (58). There are other explanations of the term pyrolysis, e.g., "Pyrolysis is a process which brings about a physical change in a molecule by means of stressing the molecule with heat. The process is carried out in the absence of oxygen and does not involve the net oxidation of the material. The molecule may be broken up, rearranged, or added to, when subjected to pyrolysis" (46), or "specific chemical change, either molecularly constructive or destructive, brought about by heat in a closed vessel" (46), or "Pyrolysis is thermal decomposition that can be achieved by heating in an inert or controlled atmosphere or by partial combustion" (19), or it can be defined simply as "the chemical decomposition by the action of heat" (53).

Destructive distillation: A form of pyrolysis defined as "the pyrolytic decomposition of a naturally occurring organic material, such as animal waste, peat, coal, wood, bone, etc., which produces char, tar, water, and carbonaceous gases" (46). The terms "destructive distillation" and "pyrolysis" are frequently confused in application. Nelson (46) explained that "pyrolysis" is most commonly used by chemists and physicists and has been accepted for the full range of molecular changes caused by heat,

while "destructive distillation" is an industrial word and describes a generally understood concept of thermal stability and thermal decomposition of organic materials.

A more easily understood explanation of the term "destructive distillation" may be found in Webster's New World Dictionary (22) where it is defined as "the decomposition of a material such as coal, wood, etc., by heat in the absence of air, followed by the recovery of volatile products of the decomposition by condensation or other means".

Biodegradation: Decomposition by biological means, especially by bacterial reaction (22).

Biological process: Activities of living organisms to sustain life, growth and reproduction.

Carbonization: To change into carbon, as by partial burning (22), or to reduce a carbonaceous material to char by pyrolysis (46).

Catalyst: Any substance used for speeding up or, sometimes, slowing down of the rate of chemical reaction without any permanent chemical change to the substance itself (22).

Cellulose: The chief substance composing the fiber of all plant tissue: cellulosic material - material made from cellulose (22).

Char: The solid, carbonaceous material remaining after pyrolysis (46), or anything charred (22).

Charcoaling: The producing of charcoal, a form of carbon, by the pyrolysis of wood or other organic matter (22, 46).

Chemical process: A process dealing with a chemical reaction, i.e., change of molecule composition.

Coking: Making coke from coal by heating with the collection of gas, tar, or other liquid hydrocarbons as by products (46), or "to change into coke" (22).

Incineration: Burning to ashes (22), or the oxidation of materials, usually with atmospheric oxygen at elevated temperature (46).

Partial oxidation: The burning of some of the material to provide heat and to remove oxygen, so as to pyrolyze the remainder (46).

Tar: A thick, sticky, brown to black liquid, obtained by the destructive distillation of wood, coal, peat, shale, etc., (22), or a bituminous material produced during pyrolysis (46).

Thermal decomposition: The reduction of large molecules to smaller molecules by heat.

Thermal composition: The production of more complex molecules by heat.

Thermolysis: Chemical dissociation of a compound by heat (22).

Thermal cracking (Cracking): To rearrange and/or reduce the molecular structure of a liquid or gas by heat (46).

4.2.2. Background

Pyrolysis, a common chemical process (19), has been known for a long time and was first used in England during feudal times to produce charcoal from wood (53). The technique later became well known and limited to the carbonization and thermolysis of waste wood from wood processing plants and to the coking of coal. This process has long been applied commercially to wood for the recovery of organic by-products such as methanol, acetic acid and turpentine in addition to the residue of charcoal (47). The material used can be any organic material that may be expected to yield gas, liquid, and solid products from the process. Materials which are difficult to dispose of can be pyrolyzed for conversion to fuel or other useful products.

Historically, the method of destructive distillation or carboniza-

tion originated in medieval times as a secret method of charcoaling within the family. The process had been used in England during the past fifty years to up-grade peat as a fuel and to obtain gas and tar by-products. During the World War II, Japan's industry, supporting the Japanese war effort, was fueled by the destructive distillation of brown coal. In the United States, techniques were developed for coking operations to supply the needs of the steel industry and to meet the demand for combustible gas and smokeless fuel in private homes (46).

The process has recently been applied to the disposal of municipal waste and industrial refuse. Therefore, as a method of waste management, pyrolysis is quite a new process. A review of literature has yielded few references to the use of pyrolysis as a waste treatment process (46). Only one report dealing with crop residues (58) was found during the period of this study. Statistics relating to pyrolytic work in the early period, i.e., prior to its application to waste management, has not been located in the literature.

The application of pyrolysis to waste management has been suggested for two reasons:

- (i) the potential of pyrolysis in converting carbonaceous materials to some useful products suggested the idea of applying the process to the treatment of nonhomogeneous municipal trash and sewage sludge (46), and
- (ii) the constraint pertaining to the sanitary landfill and incineration methods of waste disposal made it necessary to search for new techniques and pyrolysis appears to provide one solution to overcome the inherent problems of these two methods.

Currently, pyrolysis is considered not only as a technique to overcome the waste disposal problem, but also as a method for conversion of organic wastes into useful products, which are potentially useful as new sources of energy (53).

4.2.3. Review of Literature

Theoretically, "by pyrolysis at elevated temperatures, the wastes are converted into useable or more manageable solid, liquid, and gaseous forms without contributing to land, air, or water pollution" (57).

These products are profitable and are possibly a basis to justify the use of pyrolysis as a method of waste treatment, e.g., solids, may be placed in landfill, applied as a soil conditioner, briquetted for fuel and used as filter medium; liquid may be a source of usable chemicals; and gas can be used as the source of heat for the pyrolytic reaction.

Pyrolysis is not limited to solid refuse. Sewage sludge has also been carbonized, and the end product "smolder char" used to clarify the effluent of the sewage treatment plant (46). Experimentally, three pyrolysis procedures have been employed in research programs (19), i.e., bomb pyrolysis, long-tube pyrolysis and a process using a rotary glass device. The third procedure could not be used for quantitative recovery measurements.

The pyrolysis process is affected by such variables as the type or organic material burned, rate of heating, and the ultimate temperature attained by the residues produced (53). A number of research projects have been undertaken to determine the effect of these variables and also to determine, on the basis of the value of the products, if it is an economically feasible process (19, 53). These works have been applied

to process three different types of waste; municipal, industrial and agricultural. Schlesinger (58) stated that agricultural wastes have been considered many times in the past as a potential for the supply of energy by the conversion of cellulosic wastes to a liquid petroleum-like product that could be refined to various fuel oils.

Riddle (53) completed a review of literature in the utilization of municipal and industrial wastes. His paper gave a description of the recent development of pyrolysis as a method of solid waste disposal. He concluded that a pyrolysis unit should be less expensive than the incineration system and is less expensive with respect to the ultimate conservation of resources. The by-products are potentially useful as new sources of energy. However, pyrolysis techniques still have a problem of complexity and the associated cost of separating organics from non-organics prior to pyrolysis. The Engineering Experimentation Station of the Georgia Institute of Technology has been working in the area of conversion of agricultural wastes by pyrolysis for about six years (31). Starting from the first pilot project in 1968 which was designed to convert peanut hulls to a char and combustible gas, the work has resulted in a commercial operation for the conversion of sawmill waste to a marketable product of char. Other products such as oil and gas are used in the drying systems associated with this process (31). The U.S. Environmental Protection Agency has also studied the disposal of cattle feedlot wastes by pyrolysis. Garner and Smith (19) who carried out this research reported that the yield of the combustible mixture produced was 8.6% H_2 , 10.9% N_2 , 16.0% CO , 38.9% CO_2 , 12.9% CH_4 , 0.3% C_2H_4 , and 1.8% C_2H_6 . This combustible mixture is equivalent to 2 to 3 million Btu/ton (0.6 to

0.8 million kcal/mton) of dry manure.

The most interesting information related to the objective of this thesis appeared in the report of the Bureau of Mines of the United States Department of Interior which have been carrying out pyrolysis research for a considerable length of time (53). Information resulting from pyrolysis techniques developed at the Bureau of Mines are shown in Table 4.1.

Table 4.1 also contains data on rice straw which is one of the cereal crop residues being studied for energy recovery feasibility in this thesis. The dry weight composition of rice straw was found to be 36.3%C, 5.5% H, 39.7% O, 0.6% N, 0.1% S, 17.8% ash. The moisture content of the straw was 7.4%. The composition values for hulls are close to those of rice straw.

Pyrolysis techniques developed at the Bureau of Mines were first setup to determine the yield and quality of the products from coal (57). The Bureau of Mines has applied the pyrolysis technique to the conversion of several waste materials to products that could be burned cleanly and converted to energy (59). Typical waste materials that were pyrolyzed include scrap tires, municipal refuse, wood waste, battery cases, sludge and manure (59). Products from the process are a combustible gas, tar and oil, and solids which also have an appreciable heating value. The final residue is usually only a small fraction of the original waste in both weight and the volume (59).

4.2.4 Technology and Design Approach

A review of literature has shown that the important factors affecting the pyrolysis process are temperature, moisture content, and pressure. Other factors to be considered include the presence of a

TABLE 4.1

Products of Pyrolysis

Description	Types of Wastes						
	Bovine Waste ¹	Rice Straw ¹	Hulls ¹	Pine Bark ¹	Municipal Waste ²	Raw Sewage ²	Heil mill Industrial ³
Temperature, °C	900	200-700	200-700	900	900	500-900	900
Yield per ton of waste							
Gas, cu ft	13,940	5,981	5,872	20,154	17,741	9,099	14,065
Oil, gal	13.0	11.0	11.8	5.5	0.5	23.2	0.02
Ammonium sulfate, lb	58.3	7.3	*	8.8	25.1	40.2	22.9
Aqueous, gal	65.8	60.3	76.3	29.4	113.9	64.1	68.5
Residue, lb	726	800	800	630	154	576	618
Composition of gas, vol %							
CO ₂	24.5	8.6	12.1	11.5	11.4	*	11.7
CO	18.0	40.0	34.2	31.0	18.1	*	18.2
H ₂	27.5	14.4	15.4	38.3	51.9	*	51.1
CH ₄	22.7	26.7	31.0	16.4	12.7	*	12.6
C ₂ ⁺	7.3	10.3	7.3	----	5.9**	*	----
Others	----	----	----	2.8	----	*	6.4
Heating values							
Gas, Btu/cu ft	450	662	613	472	447	735	447

*no data available

**C₂ and heavier

1 data collected from reference (58)

2 data collected from reference (59)

3 data collected from reference (57)

catalyst, retort shape, and methods of material feeding (46, 58).

Temperature, the most important factor in determining the products of pyrolysis, has been investigated by several researchers. Discussions presented by a number of researchers are contained in the paper of Riddle (53) and also in the report of the Bureau of Mines of the United States Department of the Interior (58). It may be concluded that the higher the temperature, the greater the gas yield and the smaller the yield of solid and liquid fractions. Furthermore, temperature can also affect both the quantities and qualities of the yield.

It was observed that the moisture present can affect the distribution of yield. Therefore, the presence of moisture is needed to control the equilibrium composition. The solution to this problem is to pre-dry the feed materials to recover the moisture (58, 59).

The reaction in pyrolysis takes place at "atmospheric pressure" in the absence of air (70). This standard pressure condition probably has been adopted from standard coking practices which are conducted near atmospheric pressure. Pressure can affect the molecular structure, reaction and inter-reaction during processing. It has been observed that carbonization at reduced pressure produces more tar and less water than at atmospheric pressure (46).

By definition, catalysts can affect pyrolytic reactions in two ways, stimulating or retarding. Catalysts may be water and metals such as nickel, copper and iron. Carbon and char produced in the reaction can also act as catalysts (46).

The retort shape affects the nature of the products by the influence of the walls and the inclination angle. A horizontal retort produces more char and less tar, while a vertical retort has the

opposite effect and an inclined retort offers intermediate characteristics. The wall of the retort and the char produced can act as catalysts with different conditions for different kind of walls and different amounts of char produced. The retort shape also affects the pressure in the retort by altering the quantities of gas at different inclinations of retort (46).

Methods of material feeding are basically either continuous or batch systems. The batch-load type of retort is physically larger than that of the continuous type, and the material spends more time in the oven with batch systems than that with continuous-flow system (46). This extended time would lead to different composition of products.

For all organic materials pyrolyzed, the results are qualitatively similar with the same pyrolytic conditions since they are mostly similar in composition (46, 70).

A flow diagram for the process of pyrolysis is presented in Figure 4.2.

4.2.5 Discussion and Conclusions

(1) The investigation and improvement of pyrolysis techniques followed from the art of charcoaling and developed to the destructive distillation process for coking. Its application to up-grade peat as a fuel in Europe during the past fifty years, and to produce fuel for Japan's industry during the World War II, has today advanced to a modern method of waste disposal (46). Further consideration is now being given to the potential for conversion of waste into useful clean energy forms.

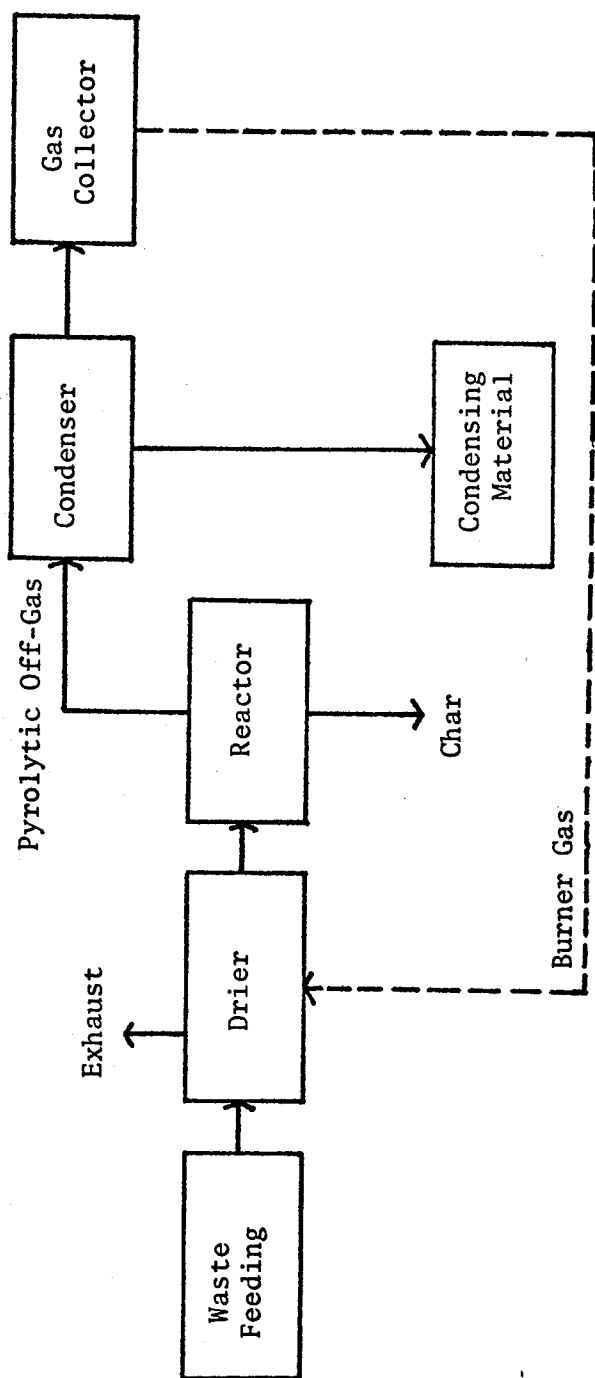


FIGURE 4.2 Flow Diagram of a Pyrolysis System *

*Figure adapted from Figure 1, Flow Diagram of Pyrolysis System of the Engineering Experimentation Station of Georgia Institute of Technology (Ref. 31).

(2) Pyrolysis techniques can be used to convert waste into potentially useful solids, liquids and gases without contributing to environmental pollution (57). It was stated in a number of reports that pyrolysis is self-sufficient in energy requirement, usually from the gas produced, and that almost all of the stored energy in the material pyrolyzed is recovered (59).

(3) However, there still exist unanswered questions in utilization of pyrolysis for energy recovery. Such questions include the gas yields from continuous plant operation, the control of moisture in the pyrolysis zone, and the appropriate design of the pyrolysis unit (59).

(4) Moisture in the material pyrolyzed can affect the distribution of products from the reaction of hydrocarbons formed. For example, the composition of gas can be shifted, and residue yield resulting from thermal cracking of oil can be affected, etc., (58, 59).

(5) A very remarkable condition of pyrolysis is that at the higher temperature, the products contain more gas and less oil (58). Other considerations include pressure, catalysts, retort shape and methods of material feeding.

4.3. Anaerobic Digestion

4.3.1 Definition of Terms

Anaerobic decomposition: A process which takes place in the absence of free oxygen. Decomposition under anaerobic decomposition is accompanied by the production of methane, carbon dioxide, hydrogen, and traces of other gases. Only a small amount of heat is released during the process (62). In biological terms, anaerobic decomposition is referred to as a

reduction of the net energy level and a change in chemical composition of organic matter caused by micro-organisms in an anaerobic environment (77). It is also known as the bacterial action resulting in a form of biodegradation (37).

Biodegradation: The destruction of organic materials by a population of micro-organisms (77), or the decomposition by biological means especially by bacterial action (22).

Biological stabilization: The decomposition of organic materials to some degree of stability which no longer can easily be decomposed by biological means, or "reduction of the net energy level of organic matter as a result of the metabolic activity of organisms" (77).

Decomposition process: Referred to as the bacterial action, or the work of micro-organisms which feed on organic raw material and which yield by-products different from the original material, as a result of their activities (62).

Digestion: The breakdown of organic matter in a water solution into simpler or more biologically stable compounds, or both (77).

Digester: A container in which fermentation or the digestion process of waste materials take place.

Organic matter: Chemical substances of animal or vegetable origin which are basically carbon structures consisting of hydrocarbons and their derivatives (77). Organic matter is referred to as a material having the characteristics of, or derived from living organisms (22).

Pollution: Unclean, impure, contaminate, dirty (22). It may be described in biological terms to be - "The presence in a body of water (or soil, or air) of material in such quantities that it impairs the water's usefulness or renders it offensive to the senses of sight, taste, or smell,

Contamination may accompany pollution", (77).

Sewage: The spent water of a community (77), or the waste matter carried off by sewers or drains (22).

Sludge: The precipitate resulting from chemical treatment, or the accumulated solids separated from liquids (77).

Slurry: The substrate which is acted upon by micro-organisms.

4.3.2. Background

The process of fermentation has been practiced for waste disposal including anaerobic digestion, aerobic digestion, composting and lagooning for many years (1). It has also been used for reducing the volume and weight of domestic sewage solids (47) and for lessening the odor normally attending sludge (65). Composting of manures to provide a fertilizer supplement for the soil is practiced in some countries. Composting takes place in the atmosphere and is called "aerobic" while "anaerobic" digestion is isolated from the influence of air. The process of aerobic fermentation results in the production of non-combustible gas (CO_2) and a large amount of spontaneous heat which can reach a temperature of 120°F (48.9°C). Normally, both of these products escape into the atmosphere. Anaerobic fermentation produces a large quantity of methane (CH_4) representing about 60% of the total gas produced with carbon dioxide (CO_2) accounting for almost all of the remainder. The gas and heat produced by the process can be kept and later utilized (63).

Methane gas is highly combustible and can be used as an energy source for domestic and industrial purposes, such as lighting, heating, cooking, running internal combustion engines, as well as providing power to run small-scale industries (63). The objective of this study is to

investigate the feasibility for energy recovery from crop residues and anaerobic fermentation will be considered as one method to be employed for its recovery.

Methane gas has been produced for millions of years from organic matter by the activity of micro-organisms. The phenomenon of this gas escaping from the earth and being ignited was observed by Volta, the Italian Scientist, in 1776 (23). Serious investigation of anaerobic decomposition was initiated in 1857 when Metcalfe attempted to digest wastes into "natural" gas from the Austin tank (23). The work has been continued by many engineers and scientists since that time. Methane gas produced from a well designed septic tank operated by Donald Cameron in 1895 was collected and used for the street lighting in the vicinity of the plant at Exeter, England. Methane gas produced from manure-digesting plants built in 1920 by Lord Iveagh in England, was used for heating the digesters in the winter and also for cooking in the dwellings nearby (35).

Many anaerobic digesters have recently been built and operated in many countries. A recent survey completed by the World Health Organization stated that "many installation for digesting and decomposing farm manures and wastes and recovering combustible gas and humus had been set up in Algeria, France, Italy, and India, as well as Germany by 1945" (62). In Germany, during and immediately after the World War II, the shortage of fuel led farmers and engineers to develop their own alternative sources of energy. A number of gas plants were constructed to produce gas from the organic matter of dung and other animal wastes. In Taiwan, following the initiation of a hog improvement program some years ago, simple methane gas generators operating under anaerobic conditions were built and by

1971 had grown in number to 7500 operating units (50). A gas plant was also reported to be in operation on a farm at Johannesburg, South Africa (62). The development of anaerobic bio-gas plants in India as a means of solving a fuel shortage problem in rural areas has an attractive potential. In this region, imported petroleum fuel prices are high, transport facilities are limited and the general practice of burning cattle dung cakes has led to a serious health problem for local people. Various designs together with modifications have been tried with the objective of improving the functional operation of systems and also to establish design criteria applicable to climate variations in India. India has made marked progress in developing the bio-gas plant as a means of exploiting the energy recovery potential from the organic content of waste material. Much research work has been completed and today there are over 2500 bio-gas plants (62) generating methane gas in India.

4.3.3. Review of Literature

The anaerobic fermentation process has been in use for many years for the primary purpose of reducing and stabilizing the volume of solids in domestic sewage during treatment. Domestic sewage treatment has the primary objective to meet requirements for sanitary disposal and gas production associated with the process is of secondary interest only. The use of the anaerobic digestion process for fuel production as a primary objective has been suggested but not developed (47). There were the displays of utilizing wastes for energy in Vienna, 1873 and in London, 1951. Since around 1930, research work on the bacterial degradation of cow dung and other organic farm wastes have been going on in many countries to improve the composting process for converting fresh dung into farm

manure. The method was later developed for the production of a combustible gas by-product by speeding up the fermentation and decomposition (62).

The process of anaerobic fermentation results from bacterial degradation of organic wastes fed into a system devoid of oxygen. These bacteria are quite sensitive to the environmental conditions in which they live. Higher temperatures are favourable to decomposition while moderate temperatures give lower gas production. The digestion process does not function at freezing temperatures (62). Anaerobic decomposition is affected not only by climatic conditions but also by other environmental factors and the waste composition (48). Digestion of farm animal and crop wastes is being practiced in Europe, Africa, India, Taiwan and Australia for conserving the fertilizer value of the wastes and for recovery of methane gas as a source of power for the farmstead (35, 62, 65). In North America, few digesters have been constructed for farm-scale operation. Since anaerobic digestion units have operated successfully in warm-climate regions, there is a need for investigation and experimentation to determine the feasibility of operating anaerobic digestion systems on Canadian farms, particularly during the winter months (35, 36, 37).

Attempts to exploit energy recovery through anaerobic digestion of wastes has led to a number of research programs in India. Laboratory work was initiated by Dr. S.V. Desai in 1940, to determine certain principles of design for the construction and operation of the digesters and a considerable number of investigations have followed. For example, Professor N.V. Joshi, in 1946, introduced a digester for a capacity of 20 to 50 cubic feet (566 to 1416 litres) of gas per day by fixing the inlet at the bottom instead of the top of the fermentation tank as in

Dr. Desai's model. Jashbai J. Patel, introduced the compact digester unit by combining the fermentation tank and the gas holder into one unit. His work considerably simplified the installation and reduced costs. Patel's developments were complemented by the work of Mr. Satish Chandra Das Gupta and Swami Viswakarma. The Gobar Gas Research Station, Ajitmal, Etawah (U.P.), India was founded in 1960 to evaluate the performance of gas plants for different designs and sizes. The program confirmed that it is possible to design plants to perform optimally under many different conditions. Ram Bux Singh who has been in-charge of a research station for 10 years has compiled activities and related results obtained at the station into two books, "Bio-Gas Plant" (62) and "Some Experiments with Bio-Gas" (63). Information given in Tables 4.2 and 4.3 following are of much interest as it relates to the study of this thesis.

In Taiwan, climatic conditions are favourable to the operation of an anaerobic digester because of the warm temperatures. During the past few years, under a program sponsored by The Chinese-American Joint Commission on Rural Reconstruction (JCRR), Taiwan farmers have installed 7500 digester units using hog dung and chicken-droppings as raw materials. Their operation has proved to be quite successful and more units are being installed by the farmers throughout the country (50).

In North America, the installation of anaerobic digestion has been impeded by cold winter weather which is not conducive to the process of fermentation, and by cheap alternative sources of fuel. Up to the present, only a few anaerobic digesters have been installed on farms for the recovery of energy and using animal wastes as the source of raw materials (37). However, interest in the conversion of organic wastes

TABLE 4.2
Gas Production by Months per Pound Bullock Dung Added¹

Months	Mean monthly temperature °F	Quantity of bullock dung added, lb	Water added lb	Volume of gas cu ft	Gas production per lb of dung cu ft
January	36.8	4.996	4.996	2.670	0.538
February	61.4	4.442	4.442	2.950	0.664
March	71.3	4.854	4.854	3.740	0.771
April	76.3	3.662	4.662	4.960	1.064
May	82.4	4.746	4.746	5.830	1.228
June	86.6	4.585	4.585	6.510	1.420
July	83.2	4.914	4.914	6.390	1.330
August	82.1	4.848	4.848	6.110	1.260
September	80.6	4.593	4.593	5.540	1.206
October	78.5	4.722	4.722	5.290	1.120
November	66.7	4.575	4.575	4.020	0.880
December	62.6	4.908	4.908	3.530	0.719

By Dr. C.N. Acharya, Indian Agricultural Research Institute, New Delhi.

¹Ram Bux Singh, Bio-Gas Plant, Gobar Gas Research Station, Ajitmal, Etawah (U.P.), India, p. 15.

TABLE 4.3

Quantity and Quality of Gas Produced From Selected Dry Materials¹

Materials	Gas per lb of dry matter cu ft	Percentage of Composition		
		CH ₄	H ₂	CO ₂
Dry leaf powder	7.2	44.44	10.78	44.76
Sugarcane thresh	12.0	45.44	10.23	44.33
Corn stover	13.0	45.94	10.26	43.83
Activated sludge	10.0	43.82	11.82	45.90
Straw powder	15.0	46.42	9.88	44.70

¹Ram Bux Singh, Bio-Gas Plant, Gobar Gas Research Station, Ajitmal, Etawah (U.P.), India, p. 18.

into energy for agriculture is increasing. A number of research projects are in progress to find the optimum conditions for the successful operation of anaerobic systems under local area environmental constraints. Dr. J. Pfeffer (49) of the Department of Civil Engineering, University of Illinois, completed a laboratory study using a 0.53 cubic feet (15 litres) reactor operating in a constant temperature room. Shredded residential refuse was used as the substrate for the entire study. Results from his laboratory study are shown in Tables 4.4 and 4.5.

In Canada, research work is in progress under the direction of an interdisciplinary committee of faculty members at the University of Manitoba. Their objective is to establish the feasibility of generating methane gas by anaerobic decomposition of livestock wastes and the usage of the gas produced (65). Laboratory investigations were undertaken using three different loading rates in six digesters having the capacity of 0.14 cubic feet (4 litres) each. These digesters were seeded with digesting sewage sludge and operated using hog manure with two different retention time and varying constant room temperatures in the mesophylic range. Sparling (65) in reporting the results of laboratory studies stated that "Gas production from 7.7 to 16.8 cubic feet of gas per pound of volatile solids destroyed with a gas composed of 57 to 60% methane was found for hog wastes". He also reported that at normal high rate digestion loadings, no ammonium toxicity interference affected the operation and that antibiotics were not a problem. Figure 4.3 following shows the results of this laboratory study.

The research work at the University of Manitoba is now proceeding in a pilot plant at the Glenlea Research Station located 15 miles (24 Km) south of the City of Winnipeg, Manitoba, where the digesters handling

TABLE 4.4

Gas Production from Shredded Residential Refuse

(cu ft/lb Dry Solid)¹

Temperature °F	Retention Time (Days)					
	4	8	10	15	20	30
95.0	1.40	2.30	2.58	2.86	2.95	3.05
104.0	2.33	2.98	3.20	3.60	3.85	4.10
105.8	2.49	3.09	3.25	3.71	3.95	4.20
107.8	2.59	3.14	3.33	3.74	3.95	4.20
109.4	2.58	3.09	3.26	3.67	3.82	4.09
113.0	2.08	2.55	2.70	3.05	3.14	3.36
118.4	2.64	3.14	3.33	3.57	3.82	4.06
127.4	3.33	3.88	4.07	4.29	4.51	4.70
132.8	3.74	4.20	4.35	4.54	4.75	4.88
140.0	4.23	4.49	4.57	4.79	4.93	4.96

¹ J. Pfeffer, "Processing Organic Solids by Anaerobic Fermentation" in Proceedings International Biomass Energy Conference, Winnipeg, Canada, May 13-15, 1973, P. XII-9.

TABLE 4.5

Gas Composition at 95°F (35°C) and 140°F (60°C)¹

Reactor number	95°F (35°C)			140°F (60°C)		
	Retention Time-Day	CH ₄ %	CO ₂ %	Retention Time-Day	CH ₄ %	CO ₂ %
1	4	69.7	30.3	3	53.5	46.5
2	4	69.8	30.2	4	55.0	45.0
3	6	64.3	35.7	6	51.9	48.1
4	8	58.6	41.4	8	50.2	49.8
5	10	57.2	42.8	10	52.3	47.7
6	15	53.8	46.2	15	53.5	46.5
7	20	53.5	46.6	20	49.1	50.9
8	30	53.8	46.2	30	53.7	46.3

¹J. Pfeffer, "Processing Organic Solids by Anaerobic Fermentation" in Proceedings International Biomass Energy Conference, Winnipeg, Canada, May 13-15, 1973, p. XII-9.

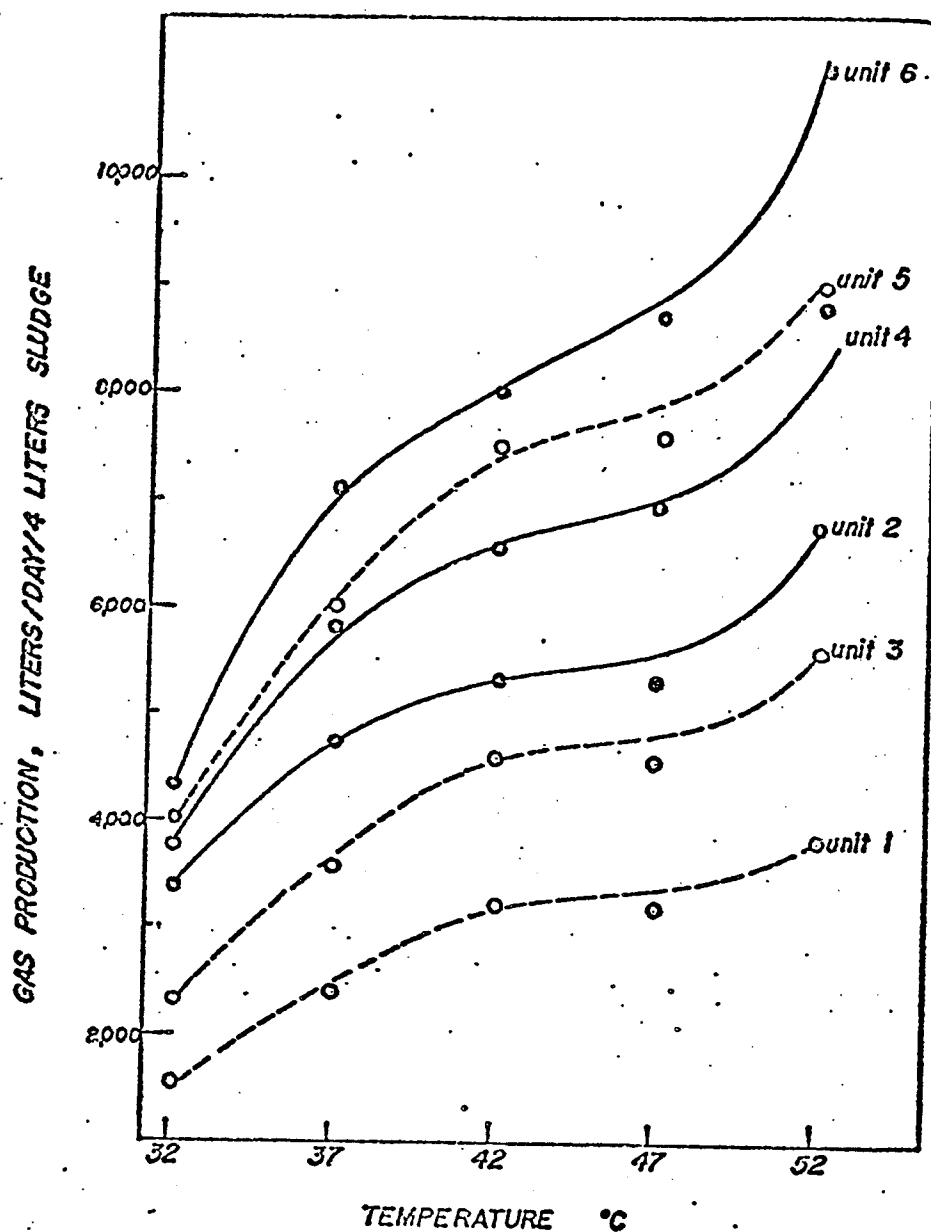


FIGURE 4.3 Gas Production in litres/day/4 litres (0.14 cu ft) Sludge as a Function of Temperature in Hog Manure Digestion
 Solid lines indicate 15-day retention time
 Dotted lines indicate 10-day retention time
 Units 1 and 2 have 0.15 lb VS/cu ft/day (2.40 gm VS/litre/day) loading rate
 Units 3 and 4 have 0.20 lb VS/cu ft/day (3.20 gm VS/litre/day) loading rate
 Units 5 and 6 have 0.25 lb VS/cu ft/day (4.00 gm VS/litre/day) loading rate (Ref. 65).

the wastes from 75 hogs are currently in operation.

4.3.4. Technology and Design Approach

The process of anaerobic digestion is a highly complex series of reactions brought about by a mixed culture of bacteria. Taiganides (74) stated that "Under proper conditions these bacteria can be cultivated to a high degree of activity within a few weeks, and then be maintained at this level indefinitely". He also claimed that "The process can be carried out within a wide range of temperatures, provided the temperature is maintained at a constant level."

Under anaerobic conditions, the process of digestion is considered to be basically a two-stage process in which organic matter is fermented to produce fatty acids which are converted into methane and carbon dioxide. In the first stage which is referred to as "liquification", fats, proteins, and carbohydrates are converted to the simple soluble organic materials in the form of fatty acids and alcohols by a group of anaerobic bacteria known as "acid formers". The products from this stage are also known as "short-chain organic acids" or "volatile acids" together with a small amount of bacterial cells. In the second stage, referred to as "gasification", the fatty acids and alcohols are acted upon by a group of anaerobic bacteria known as "methane formers" and are converted into gaseous end products of methane and carbon dioxide with small traces of hydrogen, hydrogen sulphide, and ammonia (49, 50, 65).

These bacteria exist naturally in decaying matter and can be brought into a high degree of activity within a few weeks under the proper environmental conditions (37). For optimum conditions, both types of bacteria must be in proper balance (74). The system operation is

dependent upon the "methane forming" bacteria which are comprised of several different groups and are characterised by their ability to ferment only a specific number of compounds (49, 65).

The anaerobic digester is typically an enclosed tank sealed from the atmosphere with some means of feeding and withdrawing digestible material, and a method for collecting the gas produced. Feeding slurry and withdrawing digested material can be done by gravity flow through a pipe or by pumping. The differences in design of digesters are dependent upon the methods of feeding and environmental conditions. There are two methods for feeding the slurry into digester. One is a "continuous feeding cycle" and the second is a "batch feeding cycle". The continuous feeding cycle is designed to provide uniform gas production throughout the complete period of waste digestion and is usually operated on a definite retention time cycle. A small amount of slurry is fed daily, or at some interval, into the digester so that there will always be some fresh slurry in the digester producing gas at a good rate. The batch feeding cycle is designed for fermenting materials such as vegetable wastes, that do not flow through pipes easily as well as for liquids. For this cycle, the digester contents are withdrawn and reloaded with its entire volume. The cycle operation is dependent on the composition of the fermenting material and the temperature (62).

The important factors for successful operation of digesters are feed material composition (48) and environmental parameters of temperature, loading rate, solids concentration, detention period, volatile acids concentration, scum formation, essential nutrients concentration, toxic substances, pH (74), and seeding (37).

- (1) Temperature: Digestion by bacteria occurs at temperature

ranging from 32 to 140°F (0-60°C) (62). There are three temperature ranges that the bacterial action of three different groups can take place in anaerobic decomposition. These temperature ranges are: the cryophilic (below 50°F or 10°C) (48), the mesophilic (85° to 105°F or 29.4 to 40.6°C) and the thermophilic (120 to 140°F or 48.9° to 60°C) (74). In each temperature range, there are two important factors affecting the process, i.e., the rate of bacterial action, and the detention time which is required to stabilize solids. In the cryophilic range the rate of bacterial action is very slow and the detention time is long, probably in excess of a year. In the mesophilic range, the rate of bacterial action and stabilization is high and the detention time ranges between 20 to 30 days. In the thermophilic range, the rate of bacterial action and stabilization reaches its maximum at a temperature around 131°F or 55°C (48). However, most digesters operate in the mesophilic range at a temperature in the vicinity of 95°F (35°C). At the high temperatures of the thermophilic range, bacteria are highly sensitive to the environmental changes, there is difficulty in maintaining such high temperatures (74) and there is a high energy requirement to reach the temperature level (34). At temperatures beyond the thermophilic range, all decomposition stops because the high temperatures sterilize the wastes, killing the bacteria (48). Figure 4.4 shows the relationship between time required for digestion and the temperature range.

Temperature is the most important factor affecting the detention time, and quantitative gas production. It is also essential for the anaerobic digestion to have a constant temperature in the system, as methane-formers are very sensitive to temperature changes (48). A few degrees of temperature increase does not affect the digestion while

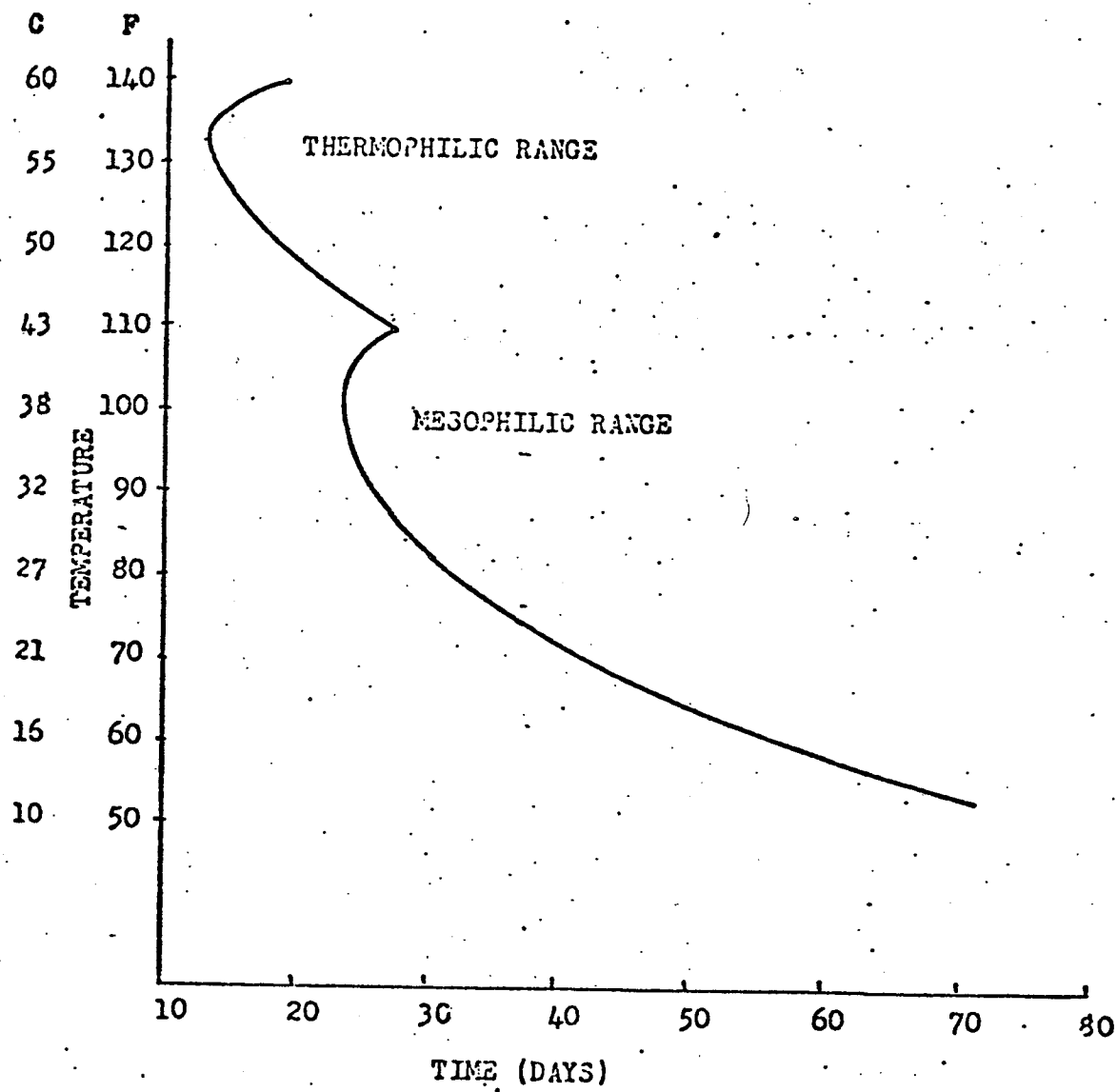


FIGURE 4.4 Relationship Between Time Required for Digestion and the Temperature Range (Ref. 48).

only 5°F (2.8°C) of temperature decrease will stop methane production without affecting acid-producing bacteria. This will lead to the excess of acids accumulation, and possible digester failure (74).

(2) Loading rate: The loading rate is expressed as the weight of volatile solids added to the digester per interval of time per unit of digester capacity (74). Since volatile solids are an indirect measure of the biodegradable organic content of a waste, successful loading rates must be found experimentally and are dependent on the solids concentration in the digester and temperature as well. However, high loading rates may increase the alkalinity and pH causing digester failure because of the slow reproduction rates of methane-forming bacteria (35, 37, 48). Lapp (35) stated that "Low feed rates result in starving the bacteria while high feed rates cause upsets because methane bacteria cannot utilize the by-products of the acid formers as fast as they are produced". Successful loading rates for swine waste digestion in Manitoba have been between 0.1 to 0.2 lb VS/cu ft/day at 95°F (35°C).

(3) Solid concentration: A sufficient quantity of water in the anaerobic digester is required for successful digestion. Water acts as a mode of transport of food for bacteria. The maximum allowable solids concentration is limited by various factors related to the composition of the matter to be decomposed (48). Animal manure generally contains from 10 to 25 percent dry solids and the solids concentration in the digester should be between 4 to 16 percent. Since the optimum solids concentration in the digester is normally about 7 to 9 percent, dilution may be required (38). The desired solids concentration is dependent on temperature and is closely related to the loading rate, Lapp (35) stated that "Low solid concentrations mean that food is

insufficient to support thriving microbial activity. High solid concentrations result in the build-up of toxic materials and again digestion is retarded";

(4) Retention period: In continuous-feed systems, the retention period can be defined in term of solids retention time (SRT) as the quantity of total solids in the digester divided by the quantity of total solids removed per day. It can also be defined in term of hydraulic retention time (HRT) as the digester volume divided by the volume of displacement (38, 74). Taiganides et al. (74) found that the digester operating at 95°F (35°C) frequently required a hydraulic retention time of 30 days. However, a range of 10 to 30 days may be required, depending on environmental conditions (37).

(5) Volatile acids concentration: The volatile acid concentrations are dependent on temperature. "At low temperature, volatile acid concentrations are low and they increase rapidly as temperature increases". (48). An increase of volatile acid concentrations results when the methane formers cannot utilize acids at the rate they are produced, and digestion stops within a few days. High acidity in the digester is mainly caused by high loading rates, reductions in temperature, and scum formation. Methane formation drops when the volatile acid concentrations expressed as acetic acid exceed 2000 to 3000 mg/litre (0.125 to 0.187 lb/cu ft). Normally, acetic acid in the operating digester ranges from 50 to 350 mg/litre (0.0031 to 0.0219 lb/cu ft). A rapid increase in volatile acid concentration can be controlled by limiting the amount and rate of substrate added [Buswell (41)] (48).

(6) Scum formation and mixing: Scum is referred to as the light weight, inert material accumulated on the top surface of the liquid in

the digester. This accumulation reduces the effective volume of a digester and obstructs the release of gas from the mixture. Scum creates a zone of substrate accumulation in which a high concentration of acid develops. The phenomenon also obstructs bacteria from making contact with their substrates. Prevention of this undesirable scum formation can be accomplished by means of mixing through mechanical rotors (agitators), by gas production recirculation, or liquid (slurry) recirculation. Mixing will maintain a homogeneous mixture of digester contents, bring bacteria into more immediate contact with the organic matter and eliminate the development of dead spots within the digester (34, 35, 36, 38, 48, 74).

Mechanical rotors are not expensive but do not function well, as there is often some scum formation in the digester. Produced gas recirculation by compressing and discharging near the bottom of the tank, provides quite good mixing of the digester contents. This system has a high initial cost but operation and maintenance cost are very low. The liquid recirculation system gives the most complete mixing, by drawing slurry from the bottom of the digester tank and pumping it for delivery at the top of the digester. The system is expensive to install and operate but it has one advantage that the sludge may be heated before pumping back into the tank (48). Mechanical agitators have been installed in the digesters located in the pilot plant in Manitoba (34).

(7) Essential nutrient concentration: A supply of nutrients is necessary for growth in a biological system. The most important elements required are nitrogen and phosphorus while many other elements are needed in trace quantities. Generally, animal wastes contain sufficient

concentrations of nutrients for good biological activity but plant wastes such as straw may lack some of the nutritional requirements. The lack of some specific elements required for growth will result in the inhibition of bacterial growth and consequently, gas production (34, 37, 38). However, high nitrogen content may occasionally produce ammonia gas which is toxic to anaerobic digestion (48).

(8) Toxic substances: The growth of bacteria is inhibited in the presence of excessive amounts of toxic substances. In biological life, an optimum quantity of nutrient elements is a stimulant for bacterial metabolism but nutrients will be toxic if present in excessively high concentrations. Salt and ammonium gas are probably the most common examples. Mineral salt concentrations in excess of 4000 ppm will retard fermentation while free ammonia can be toxic at low concentrations and may well result in the failure of the digestion system. Heavy metals are also toxic to the system. A small amount of copper is a stimulant to the enzymatic activity of bacteria but is toxic in high concentrations. Important heavy metals are copper, nickel, hexavalent chromium and zinc. The limitations of definite toxicity are difficult to determine. Toxicity can be eliminated by diluting wastes and some other specific means according to toxic substances and their characteristics (48, 74).

(9) pH and Alkalinity: The pH is an indicator of how well the digestion is proceeding. The optimum pH range for digestion is from 7 to 8. The pH below 6.5 will inhibit methane formation and a pH of below 4.5 will stop the operation of the system (74).

The alkalinity is usually ammonium bicarbonate which functions as a buffering agent to prevent the pH from dropping to a level which will inhibit the methane-forming bacteria. Low concentrations of

alkalinity may cause the methane formers to cease their activity due to the organic acids accumulation. The concentration of alkalinity desired for successful bacterial activity varies for different material digested (37, 38, 48). Control of the alkalinity and the pH can be accomplished by adding lime, if necessary.

(10) Seed: Seed is an amount of actively digesting material added to a new digester to ensure that a culture of the proper bacteria is present for start-up. Sludge from any anaerobic digester at a municipal sewage treatment plants can be used for this purpose. Without seeding, fermentation requires a lengthy start-up time. This is because the methane formers found in nature are not sufficient to begin digestion and it may take several weeks for them to multiply into a large efficient methane-forming population. Therefore, by means of seeding, start-up time can be reduced significantly. The amount of seed required is dependent upon the size of digester (36, 37, 38).

The construction and operation of a digester must be based on the design criteria for the type selected and the environmental conditions in which it must function, as size and shape of the digester do not affect digestion rates (48). The type of digesters and environmental conditions for operation have been dealt with previously. The general principles for the complete system of anaerobic digestion may be viewed from the flow sheet illustrated by Pfeffer (49) following.

4.3.5 Discussion and Conclusions

Although organic wastes are rich in fertilizing constituents, the disposal of waste without any treatment may cause a problem of pollution. Therefore, in some cases, from the public health point of

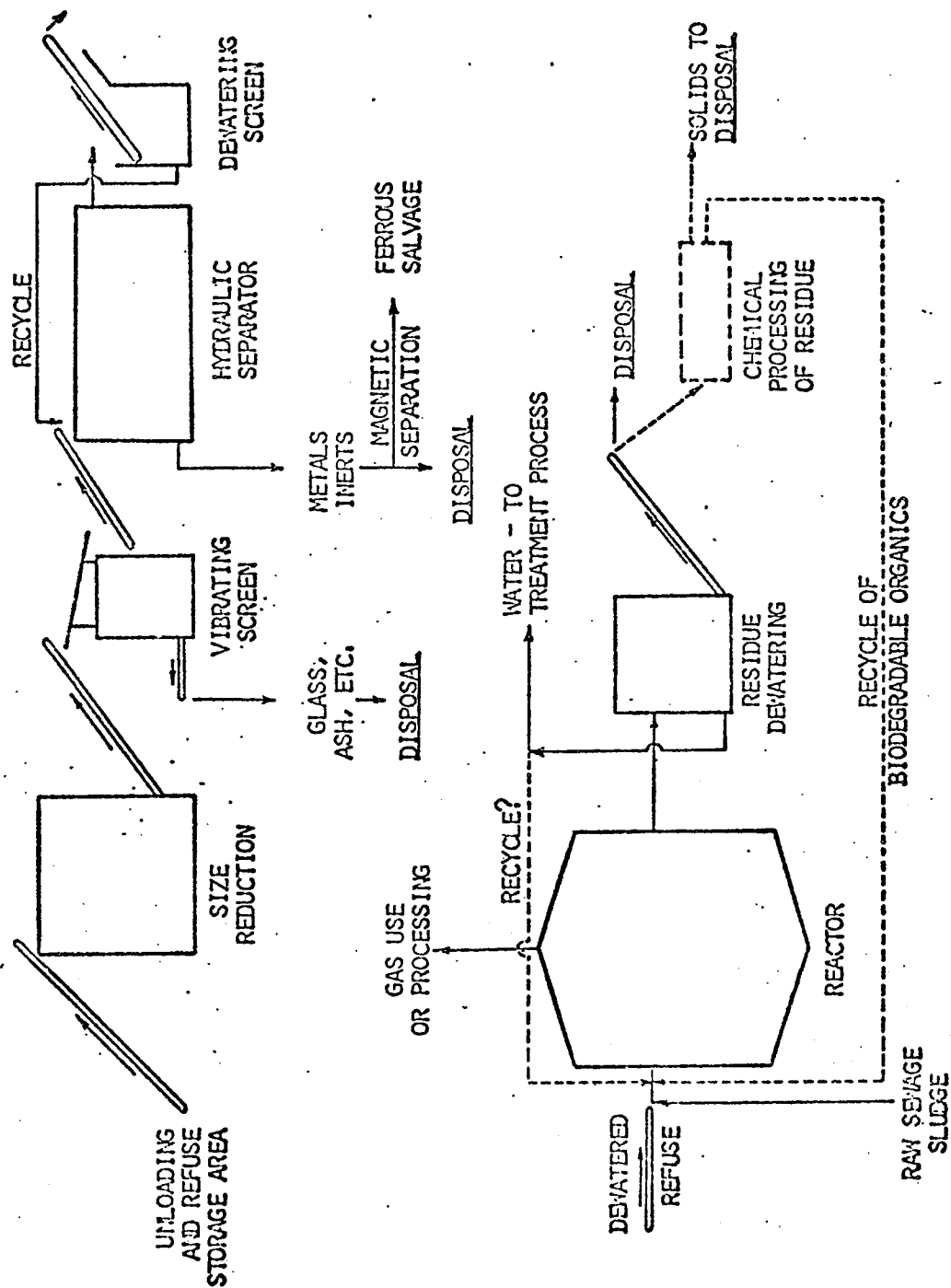


FIGURE 4.5 Typical Flow Sheet for an Anaerobic Process to Reclaim Methane from Refuse (Ref. 49).

view, wastes should be given a treatment to a safe level before final disposal (74). It has been reported that organic waste can be digested anaerobically in a proper environment. Organic wastes basically contain the same compounds, carbohydrates, proteins and fats as sewage sludge (49) which has been treated by using an anaerobic digestion system for many years (47, 74). Therefore, there appears to be no reason why crop residues could not undergo adequate anaerobic decomposition.

An anaerobic process provides not only a means of energy conservation but also a means of great reduction in the quantity of wastes for final disposal (49). Furthermore, the residue remaining after the digestion process is biologically stable (49). It is a very good plant nutrient and an excellent soil conditioner since it produces no nitrogen loss in the process (63). During the process, organic nitrogen is converted to ammonia nitrogen which is in a form more usable by plants (65). The fertilizer value of digested solids after anaerobic decomposition is higher than that of the aerobic process or of the raw waste (63, 74).

Experience and practice in municipal sewage treatment by the anaerobic fermentation process has resulted in the application of the process in some countries as a means of energy recovery from organic wastes from agriculture and domestic use. In comparing environmental conditions in which the digester may be operating, it has been noted that anaerobic digesters have been operating successfully in warm climates while only a few small scale anaerobic digesters have been installed in cold climates (37). More information is still required from research and experimentation in cold climates. Most important among the environmental parameters are temperature, loading rates, solids

concentration, detention period, volatile acids concentration, toxic substances, pH and seeding.

It has been found from the review of literature that animal wastes can be fermented successfully under the anaerobic conditions similar to the digestion of municipal wastes. Some interesting statistics are shown in the tables of this chapter particularly Table 4.3 which shows the quality and quantity of gas produced from straw. Ram Bux Singh (62) found that under the anaerobic digestion process, corn stover can produce gas in the amount of 13.0 cu ft/lb (0.812 litre/gm) of dry matter and that the gas contained 45.94% CH_4 , 10.26% H_2 , and 43.83% CO_2 . Straw powder will produce gas in the amount of 15.0 cu ft/lb (0.937 litre/gm) of dry matter and the compositions of gas was 46.42% CH_4 , 9.88% H_2 , and 44.70% CO_2 . Both materials are similar in the quantity and quality of gas produced from the process.

The anaerobic digestion is not a new technique and has been used for many years in municipal waste management practice. The process has occurred naturally since prehistoric times. Anaerobic digestion has been used successfully as a method of energy recovery from organic wastes in warm climates. It is hoped that the process will also prove to be successful in cold climates.

CHAPTER V

EXPERIMENTS

5.1 Pyrolysis

5.1.1 Apparatus

The equipment used for this experiment was a long tube constructed with some modification after the apparatus described in references (19, 31, 46, and 56). The pyrolysis system can be divided into four components including; heat supply unit, pyrolysis unit, condensing unit, and collecting unit. The pyrolysis apparatus used is shown in Figure 5.1 and Figure 5.2, while components are shown in Figures 5.3, 5.4, 5.5, 5.6 and 5.7 and are discussed in the following sections.

(i) Heat Supply Unit

The function of this unit is to provide heat to the pyrolysis tube. The unit shown in Figure 5.3 is composed of:

- (a) a propane gas tank equipped with a pressure gauge, pressure regulator, gas flow meter, copper-constantan thermocouple, and manometer to measure the delivery conditions of gas supplied to the bunsen burners. A propane gas tank was placed on the weight scale in order to determine the heat input calculated from the loss of weight of the tank during the test, and
- (b) a helium gas tank equipped with a pressure gauge, and a pressure regulator. The function of the helium gas was to flush out the air in the pyrolysis tube prior to heating.

(ii) Pyrolysis Unit

The pyrolysis unit represents a major component of the system which functions as the reactor to convert straw into gas and other by-products. The unit is shown in Figure 5.4 and is composed of:

- (a) a pyrolysis tube, three feet (0.91 m) in length and fabricated from two-inch (5.1 cm) diameter black iron pipe, which was loaded with the straw sample during each test. It was equipped with trapping tubes on both ends. The trapping tubes were made of black iron having the same diameter as the pyrolysis tube. One trapping tube, connected to the propane gas tank, had a length of six inches (15.2 cm) and was packed with ceramic (broken brick). The other trapping tube, connected to the condensing unit, had a length of 10 inches (25.4 cm) and was packed with charcoal for the inner four inches (10.2 cm) and with ceramic for the outer six inches (15.2 cm). The function of the trapping tubes was to collect the impurities in the gas produced. Trapping tubes and the pyrolysis tube were connected together by flange couplings fabricated from $\frac{3}{4}$ inch (1.9 cm) iron plates, each six inches (15.2 cm) in diameter. The tube was supported by stands at both ends, and was covered by an insulated heat shield during the tests.
- (b) A series of bunsen burners connected by a manifold was used to heat the pyrolysis tube. A maximum of 10 burners could be placed under the three-foot

(0.91 m) length of the pyrolysis tube. The temperature in the process was measured by a chromel-alumel thermocouple which was placed into a measuring tap installed in the pyrolysis tube.

(iii) Condensing Unit

A condensing unit was fabricated to collect tar, oil, and aqueous products from the gases produced. The condensation unit shown in Figure 5.5 was composed of two water-cooled condensers and two dry-ice baths. The temperature of the dry ice is reported to be -78°C (-108°F) and was not determined in this experiment (19). The water used for cooling the two condensers was flowing tap water which drained into a pail as shown. The condensate was collected in flasks installed after the condensers in the dry ice baths.

(iv) Collecting Unit

The gas produced was collected and measured by liquid displacement. As shown in Figure 5.6, the collecting unit contained two bottles, one of which contained 19 litres (0.67 cu ft) of acid salt solution. The other bottle was empty and was used to determine the volume of gas produced by measuring the volume of liquid displaced into this bottle. A three-way valve was installed within the loop between these two bottles so that each bottle could serve a reversible function in the event that the gas produced was more than 19 litres (0.67 cu ft). An off-gas tube was installed with a stopcock leading from the loop before entering the acid salt bottle and was used for collecting gas samples for composition analyses.

The connection between the pyrolysis unit, the condensing unit and the collecting unit is shown in Figure 5.7.

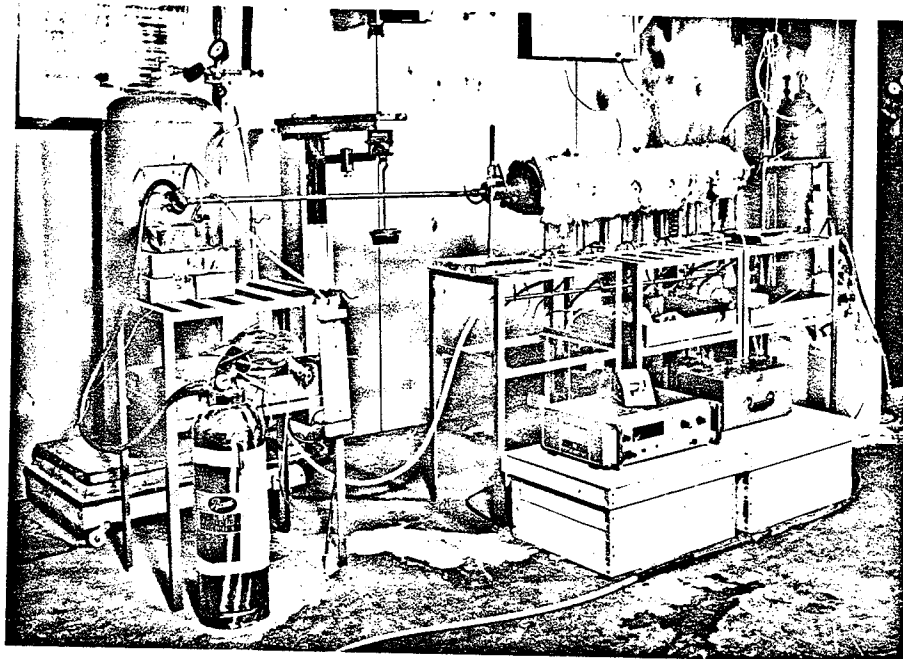


FIGURE 5.1 The Pyrolysis Apparatus

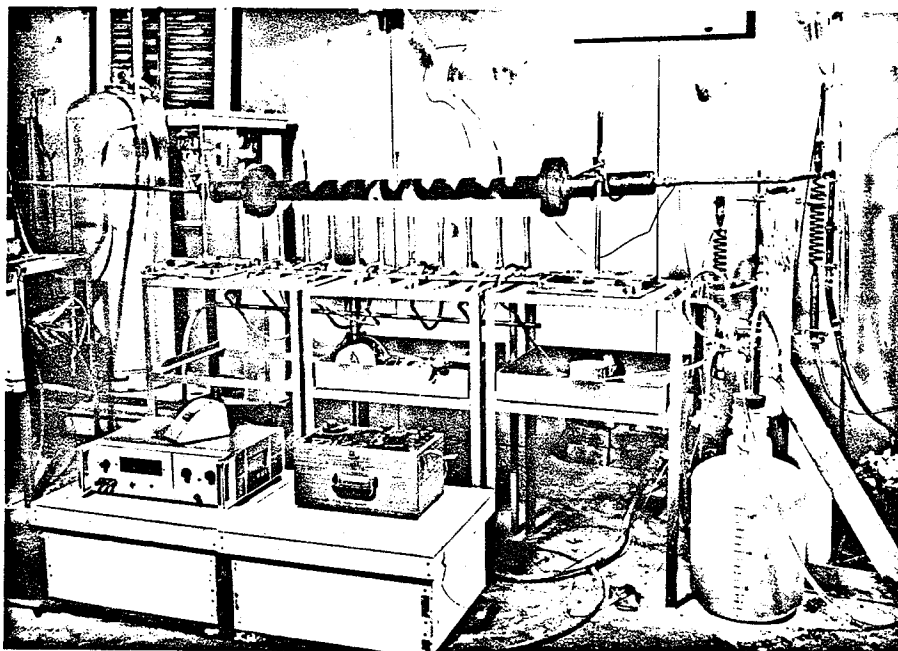


FIGURE 5.2 Heating the Pyrolysis Tube

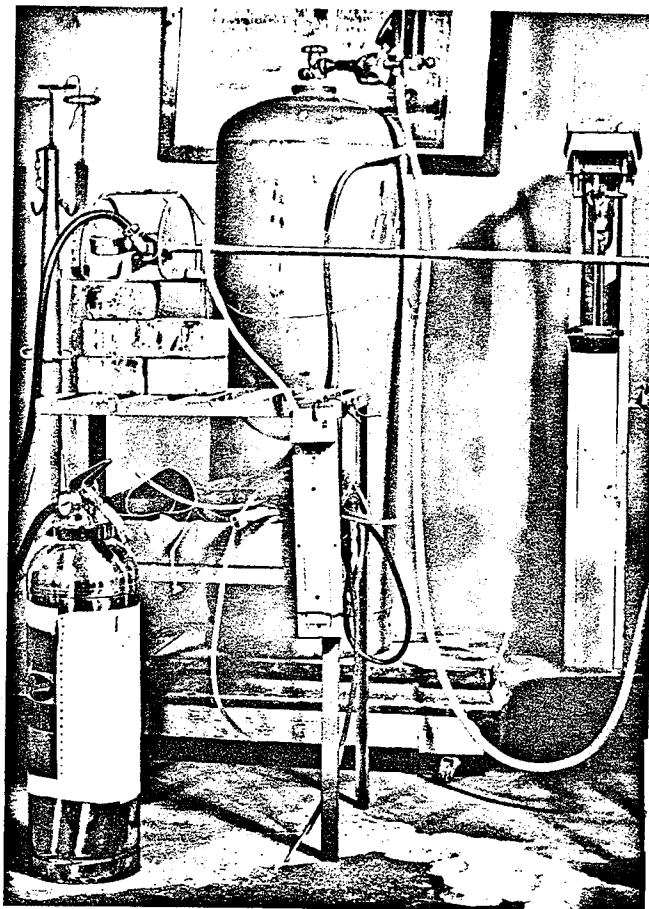


FIGURE 5.3 The Fuel Supply Unit

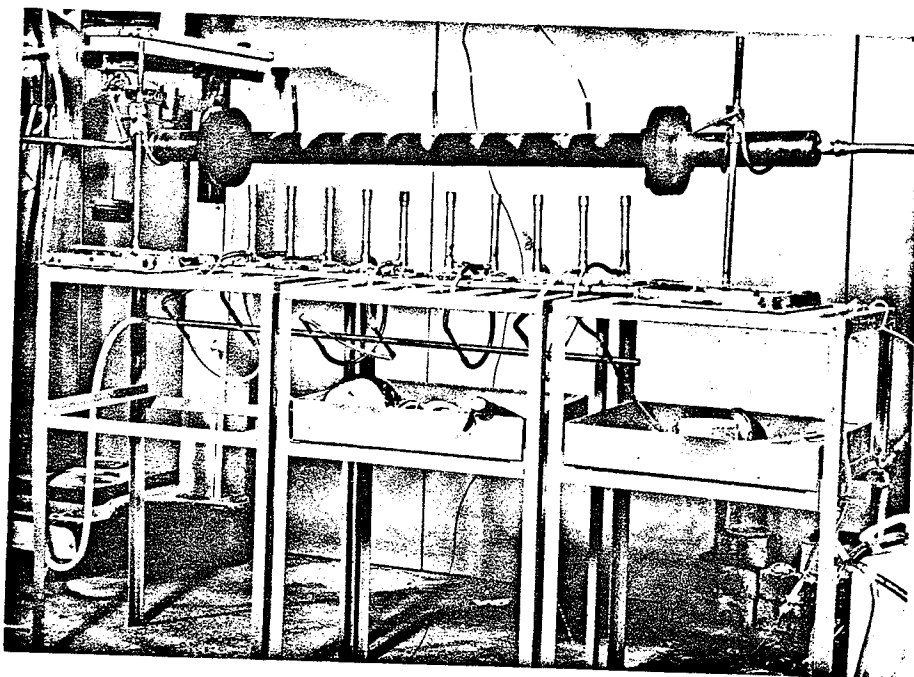


FIGURE 5.4 The Pyrolysis Tube and Burners

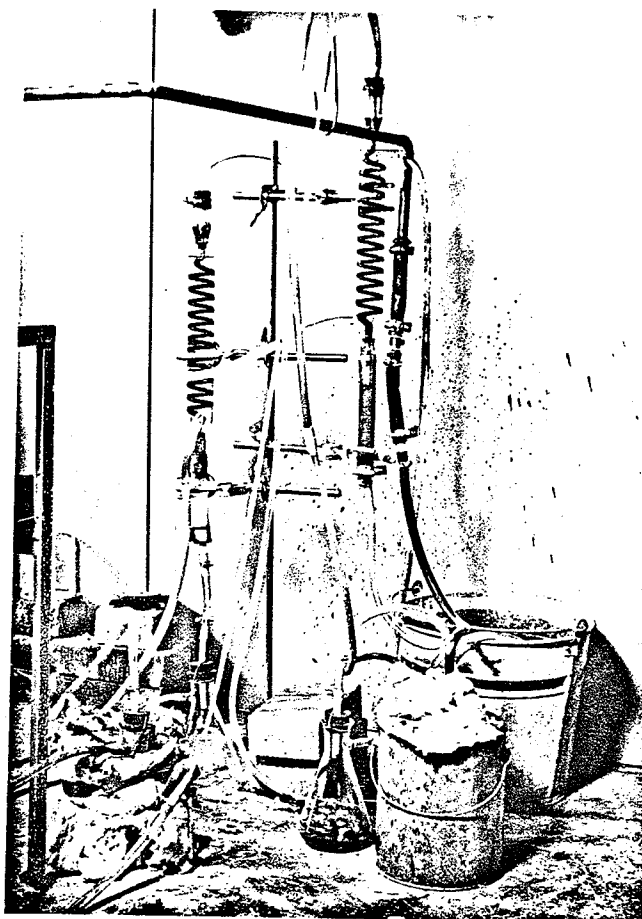


FIGURE 5.5 The Condensing Unit

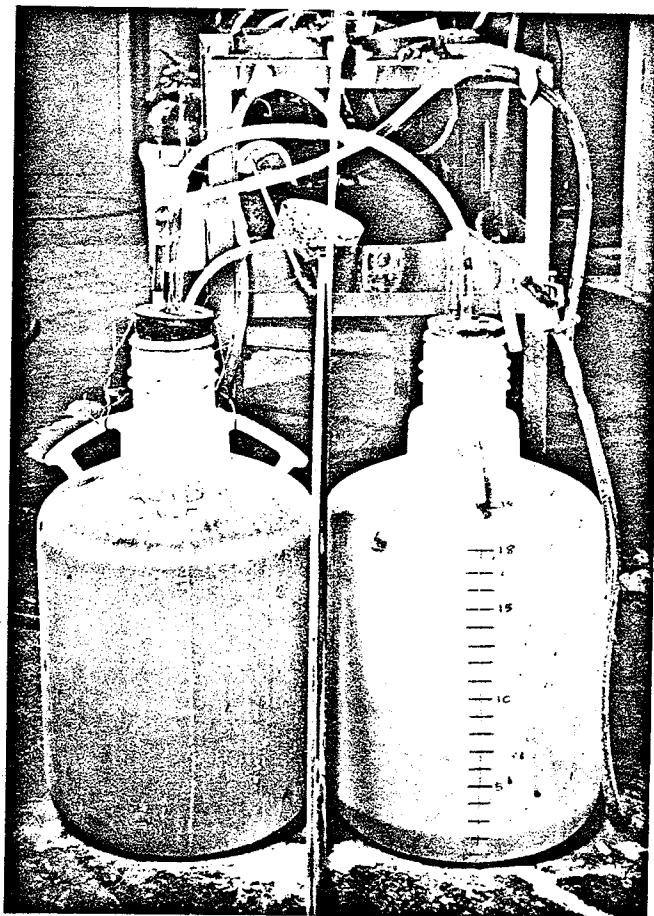


FIGURE 5.6 The Gas Collecting Unit

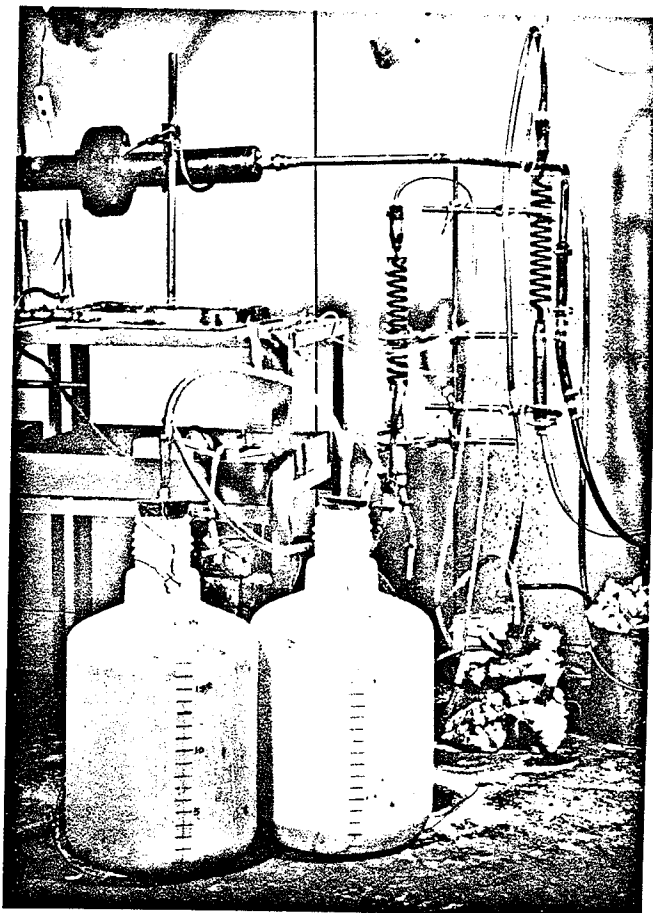


FIGURE 5.7 Connection of the Pyrolysis Unit with the Condensing and Collecting Unit

5.1.2 Material Pyrolyzed

The material used in this pyrolysis process was oat straw obtained from the Glenlea Research Station and from a nearby farm. Straw was chopped by passing it through a hammermill prior to loading the pyrolysis tube. The pyrolysis tube held 150 grams (0.331-lb) of chopped straw without any compaction. Analyses of straw samples were made to determine the moisture content and the percentages of volatile solids. The results of the analyses are noted as follows.

Moisture Contents and Volatile Solids: This analysis was made according to Standard Methods (66). Analysis of three samples yielded an average moisture content of 6.75% and an average volatile solids content of 81.77%.

5.1.3 Procedure

Straw samples were prepared by grinding in a small hammermill equipped with a $\frac{3}{16}$ -inch (0.5 cm) screen. A 150-gram (0.331-lb) sample of oat straw was used for each of the batch trials. Straw samples were placed in the pyrolysis tube through a funnel. Before starting to heat the pyrolysis tube, air was flushed out of the system by the passage of helium gas. At this time the weight of the propane gas tank and room air temperature were recorded. Thermocouples were used to measure the air temperature.

Propane gas was supplied to the bunsen burners, the quantity of which was measured by a gas flow meter expressed in maximum flow air equivalent (SCFM). The flow of propane gas was regulated at two different rates, 30% and 50% of maximum flow air equivalent. A series of bunsen burners were lit with different numbers of five, seven and ten burners for alternate tests. Temperature and pressure in the system

were recorded at several steps of the process: starting to heat, beginning of gas production, and completion of gas production.

The quantity of gas produced was measured by noting the volume of acid salt which was displaced by the gas produced. The quantity of char remaining in the pyrolysis tube was taken out for weighing to determine the volatile solids content. Other products such as tar and oil were collected, but the quantity was too small to measure. A number of gas samples were collected in the gas collecting tubes for composition analysis. The analysis of gas was carried out by Dr. W. Woodbury, Department of Plant Science, University of Manitoba.

5.1.4 Discussion and Results

(i) The Quantity of Gas Produced

Tables 5.1 and 5.2 list the quantity and characteristics of gas produced during laboratory bench trials. From the bench trials completed it can be concluded that:

- (a) the amount of gas produced from straw is a function of temperature in the process. The quantity of gas produced increased directly with higher temperatures
- (b) gas production began at a temperature of 400°F (+50°F) or 204°C (+28°C)
- (c) the rate of temperature increase also affected the quantity of gas produced. It was observed that the quantity of gas produced increased as the rate of temperature rise increased.
- (d) the test results recorded in (b) and (c) agree with observations from the review of literature in Chapter IV.

(e) from Tables 5.1 and 5.2, it was determined that;

- under a working temperature range from 60 to 700°F (16 to 316°C) the average quantity of gas produced was 1.43 cu ft/lb (0.09 litre/gm) or 2,860 cu ft/ton (89 cu m/m ton)
- under a working temperature range from 60 to 700°F (16 to 371°C) the average quantity of gas produced was 1.78 cu ft/lb (0.11 litre/gm) or 3,560 cu ft/ton (110 cu m/m ton)

(f) the quantity of gas produced from oat straw is reasonable and agrees closely with the quantity of gas reported for rice straw in Table 4.1 of Chapter IV. However, the highest production of gas from rice straw was obtained at higher pyrolysis temperatures (392 to 1,292°F or 200 to 700°C) while the ultimate pyrolysis temperature of oat straw under this experiment was about 700°F (371°C).

(ii) The Comparison of Gas Produced

Appendix B shows the results of the gas composition analysis.

The gas samples were collected by water displacement and were analysed by gas chromatography. It was reported that at least 13 different components were detected. On the basis of peak areas two components, carbon monoxide and methane, constitute 60 to 80% of the total gas detected. The average percentage of carbon monoxide was almost 40% while the average percentage of methane was almost 30%.

The calorific value of the gas produced in this experiment was not determined. Schlesinger (58) stated that the products from

agricultural wastes are in many respects similar since the wastes are cellulosic in composition. For example: "the gas has a heating value of about 500 Btu per cu ft; there is some oil and tar produced; and the residue has a heating value close to that of the feed material". From Table 4.1 of Chapter IV, the heating value of gas produced from rice straw, hulls, and pine bark are respectively 662, 613 and 472 Btu/ cu ft (5,890, 5,450 and 4,200 kcal/cu m). Therefore, the average heating value of 500 Btu/cu ft (4,450 kcal/cu m) may be applied to gas produced from oat straw under this experiment. Considering the composition of gas at 40% CO and 30% CH₄, and the calorific value of CO, and CH₄ at 323 Btu/cu ft (2,870 kcal/cu m) and 1,012 Btu/cu ft (9,000 kcal/cu m) respectively (25), the calorific value of the gas produced will be at least 433 Btu/cu ft (3,850 kcal/cu m), excluding the 30% of heating value of other gases. This value is close to 500 Btu/cu ft (4,450 kcal/cu m), reported by Schlesinger (58).

(iii) The Quantity of Products Remaining

In this experiment, products remaining after gas production ceased were char, tar and oil. The quantity of tar and oil, collected in the filtering flasks, were too small to measure under the conditions of the experiment and the quantities of these products were, therefore, not determined. The carbonaceous char of pyrolyzed straw remaining in the pyrolysis tube, was weighed after each test. The volatile solids content of the char was also determined, according to Standard Methods (66) at a temperature of 550°C (1,022°F) in a muffle furnace.

Table 5.3 shows the quantity and percentage of char remaining as well as the percentage of volatile solids present. The values show that at the ultimate temperature of 600 and 700°F

(315 and 371°C) of the process, the percentage of char remaining was between 60 to 80% of the original wet weight and the percentage of volatile solids ranged from 50 to 70% of the char. Therefore, there was a potential to obtain greater gas production had the ultimate temperature during the pyrolysis been higher. It is readily seen from Table 5.3 that when more gas was produced less char and volatile solids remained.

(iv) Thermal Efficiency

In order to increase the thermal efficiency of the unit a heat shield made of sheet metal in a semi-circular shape as shown in Figure 5.1 was installed over the top of the pyrolysis tube. The opening at the lower part of the heat shield was left open to the burners to heat the pyrolysis tube directly. To investigate the thermal efficiency of the system, two tests were conducted without a straw sample loading. One test was with the heat shield, while the second test was without the heat shield in place. The thermal efficiency was rated by recording the temperature rise versus time, since propane gas for heat input was supplied at the same rate. The results of the test are shown in Table 5.4 and in Figure 5.8.

(v) The Quantity of Heat Input and Heat Output

Table 5.5 lists the quantity of heat input and output in terms of volume of gas supplied and gas produced by pyrolysis. The quantity of gas supplied and produced is based on the standard conditions of 14.7 psia and 70°F (1.03 kg/sq cm abs and 21°C). The heating value of gases for this consideration are listed as follows:

Gas	Heating Value Btu/cu ft	Source
Propane, C_3H_8	2,509	Haslam & Russell (25)
Methane, CH_4	1,012	Haslam & Russel (25)
Hydrogen, H_2	325	Haslam & Russell (25)
Carbon monoxide, CO	323	Haslam & Russell (25)
Gas produced, (mixed)	500	Schlesinger (58)

For estimating the heat input, the heat consumed from the beginning until the commencement of gas production was excluded. The heat input shown in Table 5.5 was determined by the amount of propane supplied during the period of gas production only. The reason for this consideration is that:

- (a) it was not considered appropriate to count the heat consumed from the beginning until the start of gas production for interpretation of experimental results.
- (b) if the system was operated on a continuous feed basis, there would be no repetition in counting this amount of heat input, which may be very small.

Data show that for the ultimate temperature of 600°F (316°C), the quantity of propane supplied was 13.35 litres (0.471 cu ft), while the quantity of gas produced was 14.40 litres (0.508 cu ft). For the ultimate temperature of 700°C (371°C), the quantity of propane supplied was 20.27 litres (0.716 cu ft), while the quantity of gas produced was 18.03 litres (0.637 cu ft). The heat from the propane supplied was about five times greater than of gas produced (2,509 Btu/cu ft > 500 Btu/cu ft

or 22,325 kcal/cu m > 4,450 kcal/cu m), and the quantity of gas input and output were almost the same. These results were influenced by the following factors:

(a) the ultimate temperature of 600 and 700°F (316 and 371°C) in the pyrolysis tube was still low and, consequently, the amount of gas produced was comparatively low

(b) generally, the pyrolysis is carried out in a closed furnace system to avoid heat losses through radiation and convection. This experiment was conducted in the open air except for the heat shield provided. This shield was very inefficient and its effect was neglected. Therefore, there was considerable heat loss in the system, the time required to heat the pyrolysis tube was great, and much of propane gas supplied for heating the pyrolysis tube was wasted.

5.1.5 Conclusion

From the results of this experiment on the pyrolysis of oat straw, a number of conclusions can be drawn.

(a) Mechanical operation of the apparatus was satisfactory.

(b) Within the ultimate pyrolysis temperatures of 600 and 700°F (316 and 371°C), the yield of gas produced from 150 gm (0.331-lb) of oat straw was comparable to yields reported in scientific literature for similar temperatures. The summary of the gas yield is contained in Table 5.2.

(c) Since the ultimate pyrolysis temperature was still low and the percentage of char remaining (60 to 80%) together with its volatile solids (50 to 70%) was still high, there appears to be a potential for an increase in gas yield, by increasing the temperature of the process.

(d) The gas produced contained about 30% methane and 40% carbon monoxide while the remaining 30% of the volume was not identified.

(e) Heat input requirements were much greater than the heat output potential from the gas produced. The unfavorable heat balance can be attributed to excessive heat losses.

(f) The review of literature indicates that pyrolysis of agricultural wastes is self-sufficient in energy requirements (58). Therefore, there is good reason to continue efforts to increase the efficiency of pyrolysis as a means to recover energy from straw.

5.2 Anaerobic Digestion

5.2.1 General

The purpose of this study was to gain familiarity with the production of gas by the anaerobic process. An anaerobic gas production and collection system was set up and operated to measure gas production from the digestion of straw. No attempt was made to study the parameters affecting anaerobic digestion.

5.2.2 Apparatus

The laboratory digesters were four litres (0.14 cu ft) glass bottles. One digester was loaded with chopped oat straw while the second digester functioned as a control. Each unit consists of one digestion bottle, one gas collection bottle, and one liquid displacement bottle assembled in series as shown in Figure 5.9.

A tap for the withdrawal of effluent was located at the bottom of each digester. Gas samples were collected from an off-gas tube inserted through the rubber stopper in the gas collection bottle. Both digesters were placed into a water bath in which the temperature was

controlled at 95°F (35°C). Each gas collection bottle was filled with an acid salt. This liquid was a solution saturated with sodium sulphate and treated with sulphuric acid. The gas produced in the digestion bottle was delivered and collected in this bottle. Gas pressure caused the liquid to flow into the liquid displacement bottle and the quantity of gas produced was equal to the amount of liquid displaced for any measured time interval.

The liquid displacement bottle was vented to the atmosphere and served as a reservoir to collect the liquid displaced from the collection bottle by the evolved gas. The quantity of liquid displaced was measured daily with a graduate glass cylinder. Prior to use, the gas collection bottles were calibrated and marked to facilitate the measurement of the volumes produced.

5.2.3 Material Used

(a) Straw: Straw used for anaerobic digestion in this experiment was oat straw obtained from the same source as for the pyrolysis experiment. The straw was chopped by a hammermill prior to placement in the digester in the same manner as was done for the pyrolysis process. The straw used for this experiment had 6.75% average moisture content, 81.55% average volatile solids and 3.5% crude protein, which was the same content as the straw used in the pyrolysis experiment.

(b) Seed: A quantity of digesting sludge, obtained from the North End Sewage Treatment Plant in Winnipeg, was placed in one digester and used as a control unit. A second digester was fed with straw and was also seeded with a quantity of digesting sludge to provide a source of methane-forming bacteria. Seed placed in the straw digester represented 4.46% total solids content in the digester of which 41.43% was volatile solids.

5.2.4 Procedure

The experiment was carried out on a batch (single-feed) basis. The control digester was loaded with 4.0 litres (0.14 cu ft) of digesting sludge while the straw digester was loaded with 2.4 litres or 0.08 cu ft (60% of the total volume of a digester) of digesting sludge together with 166.7 gm (0.368-lb) of straw having a volume of approximately 1.60 litres (0.06 cu ft). The feed sludge was mixed prior to loading the individual digesters so that each digester received a representative volume of feed material. Straw was mixed with seed in the digester by shaking immediately after loading the digester with seed.

Seven days results were used for this fermentation. The quantity of gas produced daily was recorded throughout the digestion period. Samples of the digestion material were withdrawn at intervals to determine the pH, solids content, and volatile solids reduction.

5.2.5 Discussion and Results

A summary of the data observed during the seven-day period of fermentation is shown in Tables 5.6 and 5.7, and in Figures 5.10 and 5.11. Table 5.6 and Figure 5.10 show the quantity of gas produced daily from the digesters while Table 5.7 contain data on the analysis of digesting material.

For the seven-day retention time, the total gas production from the straw digester was 31.07 litres (1.097 cu ft), while 5.63 litres (0.199 cu ft) were collected from the control digester. Figure 5.10 shows that under similar conditions, the digestion process might continue for 28 days in the straw digester and for ten days in the control digester. The total quantity of gas produced throughout this digestion period would then be 67.04 litres (2.367 cu ft) from the

straw digester and 5.93 litres (0.209 cu ft) from the control digester. This is of course hypothetical and would have to be verified with further studies. The potential gas production for the 28-day hypothetical retention of 67.04 litres (2.367 cu ft) is equivalent to about 6.57 cu ft/lb (0.41 litre/gm) of dry matter for oat straw.

A further investigation into the anaerobic digestion of straw on a continuous-feed basis was later undertaken by the Department of Agricultural Engineering at the University of Manitoba. It was reported that a daily feed rate of 2.4 grams (0.0053-lb) of straw to a straw digester yielded a maximum gas production of 220 ml/hr (0.0078 cu ft/hr) while the straw control digester using the same loading rate yielded a gas production of 185 ml/hr (0.0065 cu ft/hr). These values show that the potential gas production on a continuous-feed basis would be about 6.01 cu ft/lb (0.38 litre/gm) of dry matter for oat straw.

A difficulty encountered during this study involved the build up of a straw scum formation on the top surface of the liquid, since agitation was not provided for mixing in the digester. This accumulation had the effect of reducing gas production since the organic matter was not in immediate contact to the micro-organisms throughout the volume of the digester. Mixing by mechanical means or by recycling the produced gas would probably increase the volume of gas production for any given quantity of feed material.

5.2.6 Conclusions

In this study, a single-batch feed of 166.7 gm (0.368-lb) of oat straw in the digester produced 31.07 litres (1.097 cu ft) of gas in a seven-day retention time.

TABLE 5.1

The Quantity of Gas Produced from the Pyrolysis of Oat Straw

Test no.	Propane supplied ¹ %	Number of burners	Sample weight gm	Temperature range start/produce/finish °F	Time consumed S+P/P+F/S+F ² min	Ave. rate of heating °F/min		Gas produced litre	Conclusions
						Start to produce	Produce to finish		
1.	30	5	150	69-412-515	11-8-19	31.18	12.88	23.47	13.30
2.	30	7	150	70-438-593	11-7-18	33.45	22.14	29.06	13.20
3.	30	10	150	68-426-523	12-7-19	29.83	13.86	23.95	13.80
4.	50	5	150	67-486-712	8-7-15	52.38	32.28	43.00	16.35
5.	50	7	150	70-443-705	7-7-14	53.29	37.43	45.36	16.90
6.	50	10	150	67-451-690	6-6-12	64.00	39.83	51.92	16.90

¹percent of maximum flow-air equivalent (SCFM)²time consumed, start to produce/produce to finish/start to finish

average
13.43 litres/150 gm
of the straw for the
temperature range
of 65-600°F

average
16.72 litres/150 gm
of the straw for the
temperature range
of 65-700°F

TABLE 5.2

Summary of the Gas Yield From the Pyrolysis of Oat Straw

Description	Ultimate temp of 600°F		Ultimate temp of 700°F	
	Under working conditions	Under standard conditions ¹	Under working conditions	Under standard conditions ¹
Amount of gas yield from 150 gm of straw pyrolyzed,				
litres/150 gm	13.43	14.40	16.72	18.03
litres/kg	89.58	96.05	111.52	120.26
cu ft/lb	1.43	1.54	1.78	1.92
cu ft/ton ²	2,860	3,080	3,560	3,840

¹at 14.7 psia, 70°F (1.03 kg/sq cm abs, 21°C)²short ton = 2,000 lb

TABLE 5.3
The Quantity of Char Remaining After Pyrolysis of Oat Straw

Test No.	Propane ¹ Supplied %	Number of Burners	Sample Weight gm	Temperature range start/produce/finish °F	Gas Produced litre	Char remained from the sample pyrolyzed		Volatile solids of the char ² %
						gm	%	
1	30	5	150	69-412-515	13.30	114.50	76.33	52.46
2	30	7	150	70-438-593	13.20	114.98	76.65	61.86
3	30	10	150	68-426-523	13.80	114.30	76.20	68.27
4	50	5	150	67-486-712	16.35	108.10	72.07	59.35
5	50	7	150	70-443-705	16.90	92.20	61.47	56.99
6	50	10	150	67-451-690	16.90	100.00	66.67	57.42

¹percent of maximum flow-air equivalent (SCFM)

²according to Standard Methods (66)

TABLE 5.4
Rate of Temperature Increase

Conditions	Time	Temperature
	sec	°F
1. Without heat shield	0	69
	630	590
	810	653
2. With heat shield	0	79
	528	653
	542	661
	552	669
	665	736
	783	787
	844	809

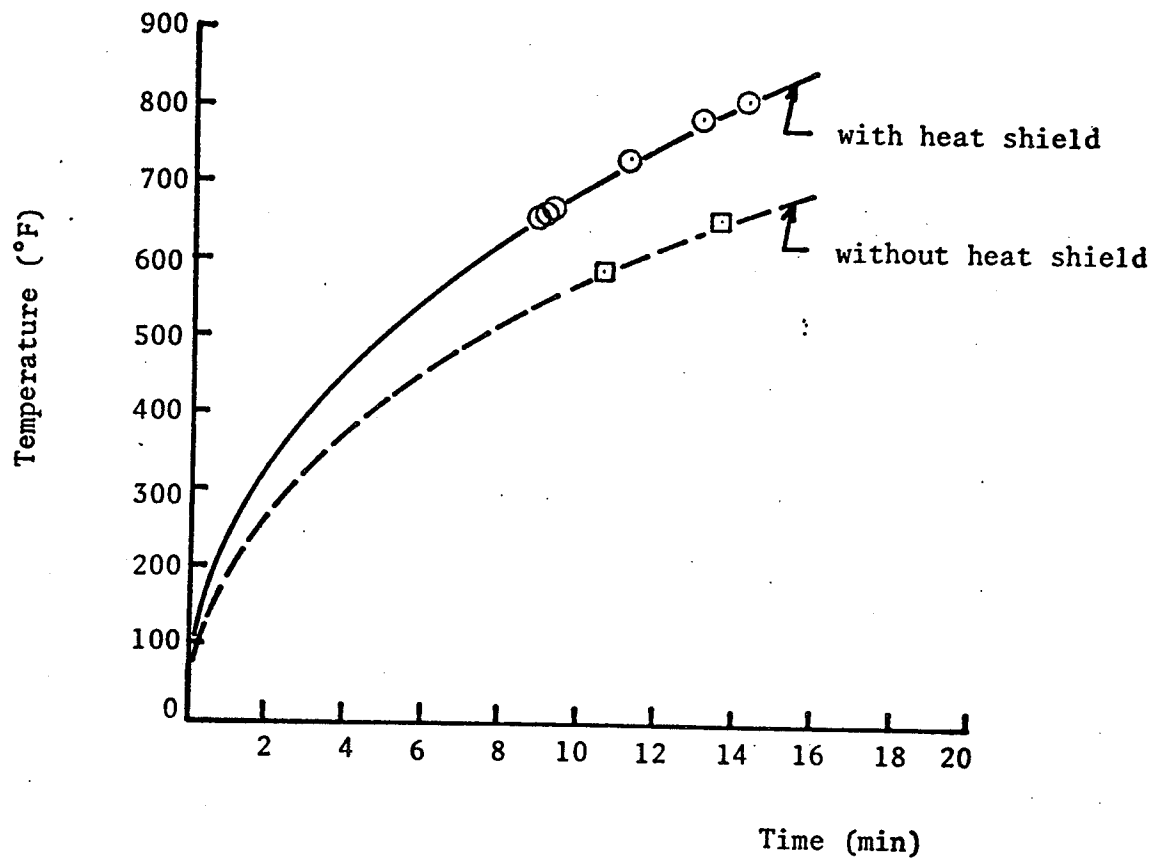


FIGURE 5.8 Comparison of Thermal Efficiency

TABLE 5.5
The Quantity of Heat Input and Heat Output

Test no.	Propane supplied ¹ %	Number of burners	Sample weight gm	Temperature range start/produce/finish °F	Time consumed S+P/P+F/S+F ² min	Max. flow metered gas litre/min	Amt. of propane supplied (P+F) ³ litre	Amount of gas produced ³ litre	Gas produced ⁴ litre
1.	30	5	150	69-412-515	11-8-19	1.82	14.56	14.28	13.30
2.	30	7	150	70-438-593	11-7-18	1.82	12.74	13.35	13.20
3.	30	10	150	68-426-523	12-7-19	1.82	12.74	14.82	13.80
4.	50	5	150	67-486-712	8-7-15	3.04	21.28	17.67	16.35
5.	50	7	150	70-443-705	7-7-14	3.04	21.28	20.27	16.90
6.	50	10	150	67-451-690	6-6-12	3.04	18.24	18.32	16.90

¹percent of maximum flow-air equivalent (SCFM)

²time consumed, start to produce/produce to finish/start to finish

³under standard conditions at 14.7 psia and 70°F (1.03 kg/sq cm abs and 21°C)

⁴under operating conditions.

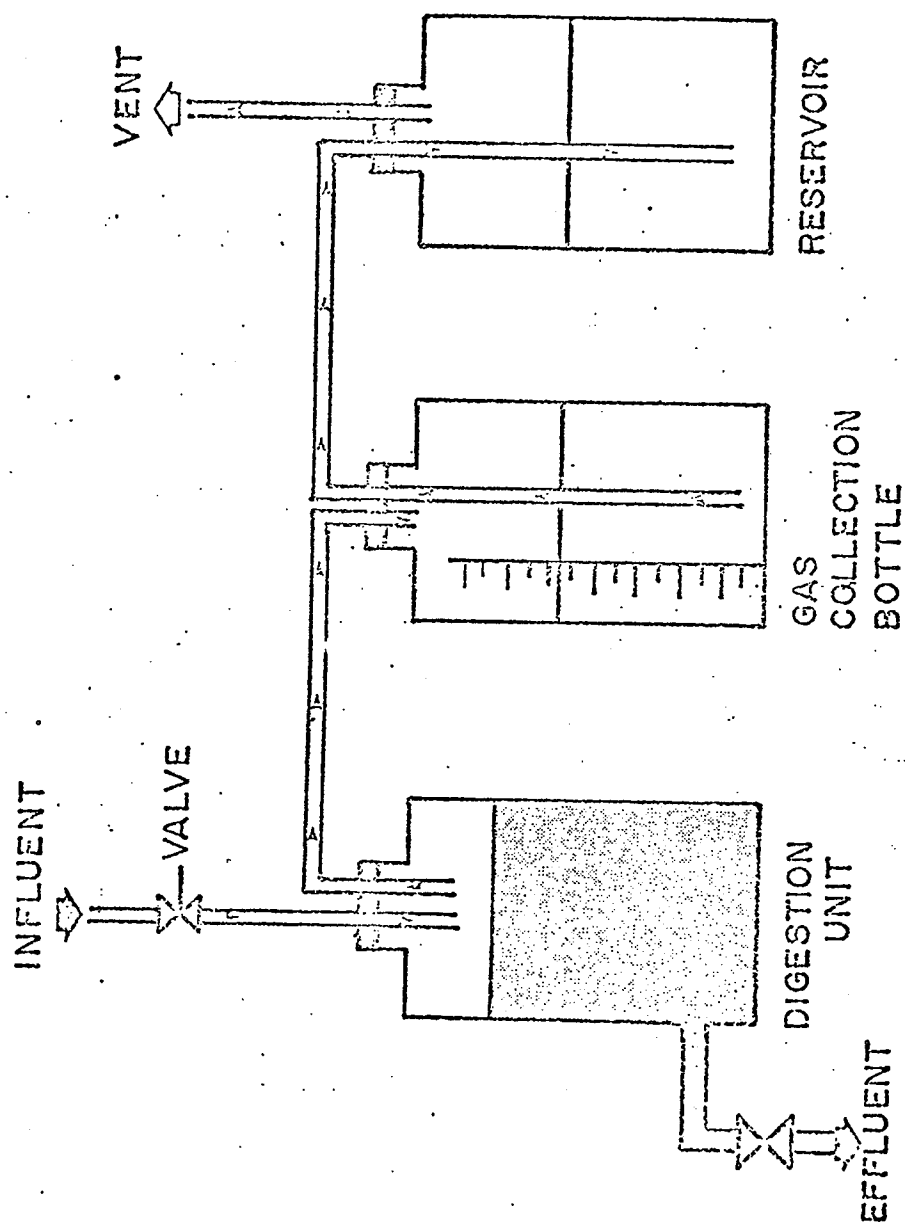


FIGURE 5.9 Schematic Layout of Bench Scale Anaerobic Digester (Ref. 38)

TABLE 5.6

Volume of Gas Produced From Digesters

Day	Straw Digester		Control Digester	
	daily gas ml	accumulated ml	daily gas ml	accumulated ml
Start	0	0	0	0
1	5,310	5,310	1,605	1,605
2	6,145	11,455	1,125	2,730
3	4,290	15,745	880	3,610
4	4,090	19,835	660	4,270
5	3,950	23,785	565	4,835
6	3,705	27,490	480	5,315
7	3,580	31,070	310	5,625

TABLE 5.7
Analysis of Digesting Material

Description	Straw Digester		Control Digester	
	Start	7 days	Start	7 days
pH	-	7.0	-	7.3
Total solid	*	*	4.46%	4.38%
Volatile solid	*	*	41.43%	38.84%

*poor results due to the difficulties in obtaining a representative volume of digesting material.

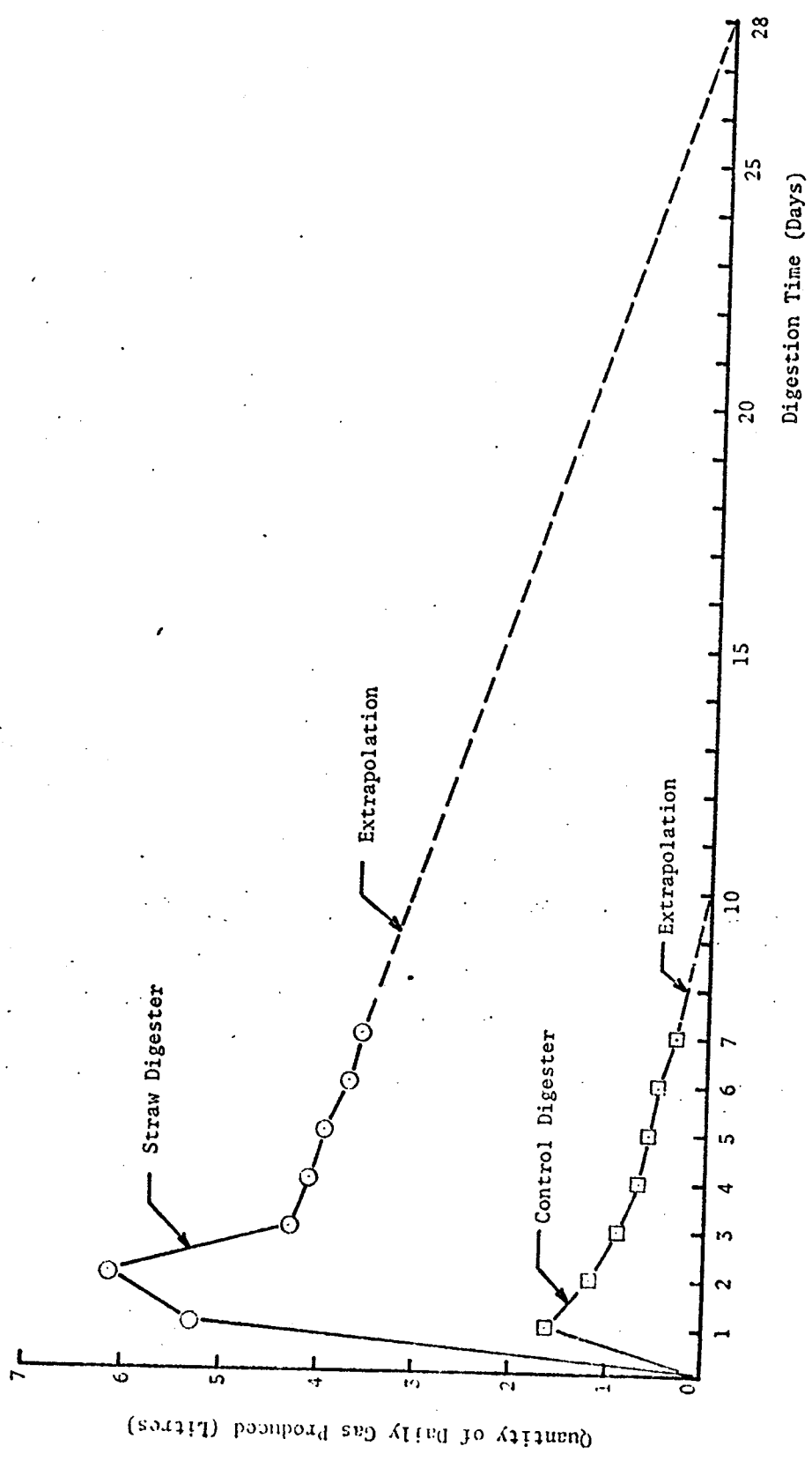


FIGURE 5.10 Daily Gas Production from Digesters

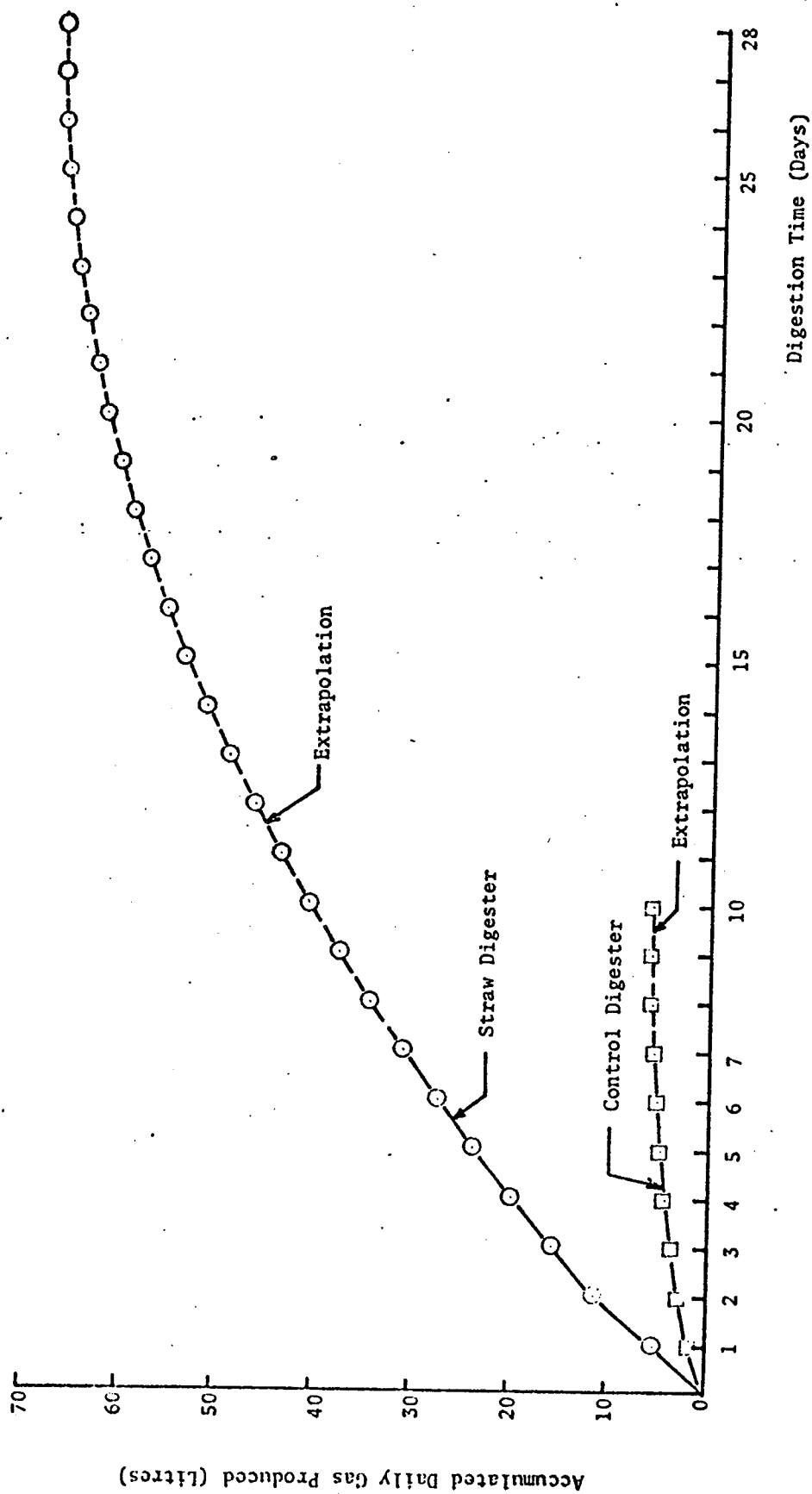


FIGURE 5.11 Accumulated Daily Gas Production from Digesters

CHAPTER VI

TECHNICAL AND ECONOMIC CONSIDERATIONS

6.1. Technical Aspects6.1.1. Materials Handling

A great quantity of straw is produced annually in Canada. This large tonnage of crop residue has been given consideration as a potential renewable resource for conversion to energy fuel (71). The values given in Chapters II and III are based on the assumption that all straw would be collected and brought to a processing plant. This assumption would not be realised since all available crop residues could not be used for energy conversion (70). It is estimated that one-half of this crop residue should be returned to the soil for fertility maintenance and further that one-half ton of crop residue is required for each animal housed (13) in beef and dairy enterprises. This means that not more than 50 percent of the total quantity of straw produced annually could be used in energy conversion processes. Moreover, there are major problems associated with the utilization of this quantity of straw. A prime problem is related to materials handling which includes such factors as collection, concentration, transportation, storage, cost, labour, environmental impact, etc. The author has concluded that very limited studies relating to feasibility and cost (13) of alternate materials handling systems for straw have been completed.

Technically, collection of straw is not a problem as it can be collected using equipment which is already available (44). Straw can be collected from the combine by using a baler and the bales can be stacked neatly into small or large storage piles. Current farm practices result in waste, first, by burning large areas of harvested stubble,

and secondly by simply leaving excess quantities of straw residue on the land. McGinnis (44) introduced two possible solutions to the problem of straw collection. First, there could be a financial incentive made available to the farmer so that a reasonable profit could be realized from straw collection. Secondly, the Clean Environment Commission may prohibit burning of crop residues which is currently enforced in some states in the United States. The latter regulation would encourage the farmer to collect straw and remove it from the fields even at very low prices. The economic collection and handling of straw is a practical problem and has to be solved as straw has to be used as a raw material. Some years ago, a committee of representatives of interested manufactures was used to promote collection and to control the quality of straw used for making strawboard in the United States (44). This might be a third approach to the problem of straw collection at the present time. Collection must be economically feasible so that crop residues will be available for processing. Crentz (10) estimated that only about 20 percent of the total organic solid wastes generated in the United States are available for processing for fuel.

Concentration is also an important problem as there are only few locations where straw is concentrated and stored to a greater extent than several hundred tons (71). Scattering of the straw available will result in higher cost of collection due to transportation, energy and labour used. Concentration of straw is not the same problem as in some other agricultural practices where wastes are concentrated as, for example, in the widespread use of animal feedlots for meat production (70). In order to overcome the collection difficulty due to the concentration problem, Stone (71) suggested that the use of a light

portable briquetting machine which could be driven to the straw stacks, or used in conjunction with a pick-up baler, would probably be the most suitable method. Knight (31) also reported that preliminary work has been undertaken toward the development of a transportable pyrolysis system at Georgia Institute of Technology. The need for transportability arise from the fact that many agricultural wastes are produced seasonally and in widely diverse locations. By applying this concept the transportation costs of the raw wastes would be minimized.

Transportation and storage would probably be a far greater problem due to the vast quantities of material required for processing (44). Straw must be transported to the plants when it will be processed. A minimum travel distance would therefore be preferred in order to minimize the costs of transportation. Straw is also produced and collected seasonally. A large storage would, therefore, be required prior to its processing. McGinnis (44) referred to the possibility of smaller on-farm biomass fuel generators proposed by Robertson and stated that this would of course reduce the transportation and storage problems but that only major centers could afford to get into the business. The other solutions proposed by Knight (31) and Stone (71), which have been referred to, can be considered as possibilities for solving these problems. It has been proposed that the associated problems of the collection and handling of the huge bulk of straw from fields to where the processing is done could best be solved by pelletizing the straw (73).

As for environmental impact, the collection and handling of straw would reduce the environmental pollution problem. It has been common practice for many years to burn the residues from large areas following harvest (44), or to break the stall in some manner, windrow

the residue, and then burn it. This practice is undesirable as it destroys much plant food which should be returned to the soil (5) and further the products of combustion are pollutants. It is also desirable that some straw referred to as stubble be left standing after harvest. This straw stubble provides protection against soil erosion and is finally plowed back into the soil for the maintenance of its fertility. However, this practice is not beneficial in all areas as it has been found that this stubble not only degraded the quality of legume hay but also depressed its yield (40). Yeck (79) estimated that of the 390 million tons (355 million mtons) of dry matter of agricultural crop residues generated annually in the United States, only 23 million tons (21 million mtons) were collected. This means only about 5.9% of agricultural crop residues were collected annually. He also stated that in 1970 about 3.6 million tons (3.3 million mtons) of crop residues from about 1.1 million acres (0.4 million hectares) were destroyed by open field burning for plant disease and insect control. This practice is already banned in some locations and alternate methods of destruction are needed. Environmental pollution problems can be reduced by introducing efficient collection methods together with incentives for the farmer.

6.1.2. Processing Alternatives

Potential energy in crop residues could be utilized as heat energy by means of direct burning, but the method is not practical for many reasons. Limitations on direct burning are (10);

- (a) energy recovery by this means is not storable,
and it has to be used as it is produced,
- (b) calorific value and the efficiency of heat energy
recovery is relatively low,

- (c) the process may result in pollution problems because residues do not burn cleanly,
- (d) the production of residues may not be distributed throughout the year and are, in fact, normally seasonally produced. Therefore, the supply of residues may be out of phase with an energy demand and residue storage would be essential, and
- (e) some raw wastes such as manure cannot be stored for long intervals, or it may require a large and expensive storage which is impractical.

A closed or minimum weather protection shelter for a high quantity of straw is also impractical.

Organic residues are convertible into replenishable clean-burning, high energy fuels (70). It is therefore desirable to convert residues into forms of clean energy fuel which can be easily stored and efficiently utilized. Storable clean energy fuel may be in the form of a solid, liquid or gas and will have a high heating value per unit weight (70). The process of conversion, quality and characteristics of products for different forms of storable energy are different as shown in Table 6.1. The chemistry of the conversion process is the most important factor that has to be investigated as a first step in energy recovery from residues (2). Because of the growing energy shortage in the United States complemented by demands for a clean environment, the Bureau of Mines of the United States Department of the Interior has been exploring three processes for converting wastes into low-sulphur synthetic fuels. The conversion processes being studied are liquefaction, hydrogasification and pyrolysis (coking) reactions (2, 10, 70).

Liquefaction is a process by which organic solid wastes are converted into fuel oil. This process was discovered some four years ago, at the Bureau of Mines, as an outgrowth of research work with coal (10). It was explained that the conversion was basically simple and that the process was similar to one used for the conversion of coal to oil (76). The process involves heating cellulose with carbon monoxide and water which is converted to an oil. By adding a catalyst such as sodium carbonate, the oil yield is increased (2). It was also found the cellulose and lignin, the main constituents of growing plants were converted to low-sulfur oil with faster reaction and completion than was coal. Since cellulose and lignin are also the main constituents of organic solid wastes, they represent potential materials for conversion to oil by the same process. The process is affected by temperature and pressure with optimum conditions ranging respectively from 300 to 380°C (572 to 716°F) and 2,000 to 6,000 psi (140.6 to 421.8 kg/sq cm), with a residence time of approximately one-half hour (10). Experimental results show that the distribution of products from this process was greater than 95% (by weight) fuel oil, while the remainder was char (see Table 6.1). The heating value of oil produced from municipal garbage was 15,000 Btu/lb (8,300 kcal/kg) (10). The economics of the liquefaction process, for example, converting manure to oil, are quite elusive at present. It depends on what the cost of the raw materials will be. Besides, its value will depend largely upon the availability of low sulphur oil from other sources (76).

Hydrogasification is a thermal reaction between hydrogen and organic solid wastes (70). The process converts wastes mostly into methane which is the main constituent of natural gas and satisfies the heating value of 900 Btu/ cu ft (8,000 kcal/cu m) which is minimum pipeline standards.

TABLE 6.1

Distinguishing Characteristics of Waste to Fuel Processes¹

Product distribution, wt %	Liquefaction	Hydrogasification	Pyrolysis
Fuel oil	>95	0	20
Gas	ca. 0	> 95 (high Btu)	50 (med. Btu)
Char	< 5	< 5 [*]	30
Conditions			
Temperature, °C	250-400	500-700	500-900
Temperature, °F	480-750	930-1290	930-1650
Pressure, kg/cm ²	100-300	70-180	1
Pressure, psi	1500-4500	1000-2700	15
Gas added ²	CO-H ₂ O or CO-H ₂ -H ₂ O	H ₂	None
Catalyst	Alkali ³	None	None

*The char formed is converted in a second gasifier to synthesis gas which is shifted to hydrogen and used in the hydrogasifier.

¹Fred W. Steffgen, "Energy from Agricultural Products". Paper presented at the 65th annual meeting of the American Society of Agronomy, Las Vegas, Nevada, November 11-16, 1973, p.6.

²The gases may be produced from solid wastes.

³Not required for most wastes at higher temperatures.

Although only a few wastes have been hydrogasified in the laboratory, work done at the Bureau of Mines showed that solid wastes could be converted to methane and ethane at conditions considerably milder than those of the same process for coal conversion. The process is affected by temperature and as the temperature is increased, the production of methane is increased, while the production of other hydrocarbons diminishes. Experiments showed that hydrogasification of solid wastes resulted in gas production at 1,000 psi (70.3 kg/sq cm), transmission pipeline pressure, and at 1,022°F (550°C). The distribution of the production was greater than 95% (by weight) of high calorific value gas and the remaining was char of less than 5% (see Table 6.1). Economic analysis of the hydrogasification process shows that the most important cost factors affecting the process are the amount of waste available, its composition and the price of pipeline gas in the area (70).

Pyrolysis is the process by which organic solid wastes are converted into gas, oil and solid fuel. The process has been fully discussed in Chapters IV and V. The purpose of referring to the process again is to note that solid fuel can be produced from organic solids wastes. From the pyrolysis process, the distribution of products shown in Table 6.1 was 20% fuel oil (by weight), 50% of medium calorific value gas and 30% char.

6.2. Economic Aspects

An economic evaluation cannot be made solely on the cost analysis of processing itself. The factors of materials handling and the price of products, e.g., fuel, from other sources must be taken into the consideration. Environmental impact is also important and must be taken into consideration. The following discussion of the economics of pyrolysis

and anaerobic digestion are mainly from the processing point of view, as other factors were previously discussed.

6.2.1 Economics of Pyrolysis

Pyrolysis, a technique used for solid-waste disposal, can be used to convert wastes into solid, liquid, and gaseous fuels without contributing to environmental pollution (53, 57). As there is only limited information available on the cost of pyrolysis (59), an assessment of its economic value is difficult. However, as a method of waste disposal, preliminary estimates indicate that the cost will be considerably less than for disposal by other means, for example, less than the reported U.S. \$8.00 per ton (U.S. \$8.80 per mton) for incineration (59). Riddle (53) referred to a report of Debell and Richardson (1971) on the cost comparisons for solid-waste disposal in the United States (excluding collection) noted as following:

(i) Common dump	U.S. \$1.00 to U.S. \$2.00 per ton (U.S. \$1.10 to U.S. \$2.20 per mton)
(ii) Sanitary landfill	U.S. \$3.00 to U.S. \$4.00 per ton (U.S. \$3.30 to U.S. \$4.40 per mton)
(iii) Incineration	U.S. \$8.00 to U.S. \$12.00 per ton (U.S. \$8.80 to U.S. \$13.20 per mton)
(iv) Pyrolysis	U.S. \$3.00 to U.S. \$4.00 per ton with by-products recovery. (U.S. \$3.30 to U.S. \$4.40 per mton).

Without by-products recovery, pyrolysis cost can be as high as U.S. \$15.00 to U.S. \$20.00 per ton (U.S. \$16.50 to \$22.00 per mton) which is higher than the operating costs for incineration. Therefore, the economics of pyrolysis is dependent mainly upon recovery of fuels (53).

An estimate of the cost of pyrolysis for different plant sizes are given in Table 6.2. These costs are all less than the cost of incineration at U.S. \$8.00 per ton (U.S. \$8.80 per mton).

TABLE 6.2
Cost of Pyrolysis¹

Plant size, tons of waste per day (wet)	500	1,500	2,500	5,000
Capital cost, U.S. \$ million	3.82	6.85	9.68	16.0
Operating cost, U.S. \$ per ton	5.79	2.76	1.97	1.25

¹M.D. Schlesinger and others, "Pyrolysis of Waste Materials from Urban and Rural Sources", in Proceedings of the Third Mineral Waste Utilization Symposium, Chicago, Illinois, March 14-16, 1972, pp. 423-428.

As a method of energy conversion, pyrolysis is thermally self-sufficient from the gas produced. Energy available in the solid, liquid, and gaseous fuel produced is more than enough to supply the energy required for the pyrolysis process. However, there are still many unanswered questions concerning processing conditions, and products. These questions relate to yields from continuous plant operation, moisture control in the pyrolysis zone, and the preference of the pyrolysis unit design (56, 59). Garner and Smith (19) in discussing the cost of pyrolysing manure did not agree that the process had economic feasibility and stated that "Pyrolysis cannot pay its way, and that a useful fuel.... oil, gas or coal....must be sacrificed to yield a product of presently questionable commercial value".

6.2.2. Economics of Anerobic Digestion

The anaerobic digestion process, a technique which has been practiced in municipal sewage treatment plants, has now come under consideration as a method for the extraction of useful fuel from farm wastes. The economics of this process are still difficult to discuss and to give firm advice as its conditions vary considerably. There are many factors involved in estimating the costs of operating on anaerobic process. These factors include local climate conditions, initial material and labour cost for the installation, type of waste involved, sources of power and heat, prices of alternate fertilizers, the cost and availability of alternate fuels, the size of the plant etc. The only thing that one can now give is advice as to the advantages and disadvantages of the systems and refer to research work being carried out (4, 28, 74).

The discussions on the economics of anaerobic processes are found to be different from various reports. The reports of Taiganides et al. (74) and Singh (62) give a positive discussion on the gas production from agricultural wastes. Taiganides et al. (74) reported in their study on anaerobic digestion of hog wastes that "on the basis of a 10-year amortization of 4% interest and a digestion temperature of 95°F (35°C), a marginal profit will be realized in hog operations producing about 10,000 hogs per year, under United States conditions". Singh (62) has estimated the cost of bio-gas plant as shown in Table 6.3.

Based on the plant size of 100 cu ft/day (2.83 cu m/day) which costs about U.S. \$400.00, with the assumptions of 20 years depreciated life, 6 percent interest, U.S. \$10.00 per year of miscellaneous expenses, Singh suggested that the entire cost of installation, against the daily gas production which is equivalent to about 1.9 litres (0.42 imperial

TABLE 6.3
Cost of Bio-gas Plant¹

No.	Size of the plant, cu ft of gas production per day	Approx. cost of the installation in India, U.S. \$	Approx. cost of the installation in U.S.A., U.S. \$	Remarks
1	100	140	400	family size
2	250	350	900	joint family size
3	500	600	1,800	farm size
4	1,250	1,500	4,000	industrial size
5	2,000	2,250	5,500	industrial size

¹Ram Bux Singh, Bio-Gas Plant, Gobar Gas Research Station, Ajitmal, Etawah (U.P.), India, p.66.

gallons) of gasoline, is recovered within four years of operation. The effluent which has been fully digested is also counted into the profit of this evaluation as it is rich in nutrient value as a fertilizer. He noted, furthermore, that the investment in larger plants will be more economical as the installation cost per cubic foot of gas production decreases with the increase in the size of plant. However, it is remarkable to note that in both reports the cost of materials handling e.g., collection, transportation, etc., was not brought into this evaluation.

Opposing views to the above discussions can be found in the reports of Batty (4) and Jones and Brown (28). Batty stated that anaerobic digestion of livestock manure may or may not be justified on the basis of fuel production alone, depending on the type of waste, the cost and availability of alternate fuels, and that many optimistic reports of methane gas production from organic waste have been misleading. He also claimed that the production of methane gas as a fuel is, at present, not economically practical in most instances. The report of Jones and Brown (28) supports the above discussion in which they stated that "the investment required to set up a plant solely to produce methane gas with all the necessary equipment has not traditionally been a viable investment. Electricity, oil, and natural gas have been cheaper to buy, but the position could change".

6.2.3 Economics of Materials Handling

Crop District No. 3 was used as a sample area to consider the economic feasibility of collecting large quantities of straw to supply an energy recovery processing plant. From statistics given in Chapter II and III, the acreage of cereal crops grown in this area is about

934×10^3 acres (378×10^3 hectares). The total quantity of straw produced annually was estimated to be $1,948.7 \times 10^6$ lb (0.9×10^6 mtons) containing a potential energy equivalent to 11.7×10^{12} Btu (2.9×10^{12} kcal). The availability of straw was assumed to be one-half of the total quantity produced annually, i.e., about 974.4×10^6 (0.4×10^6 mtons). It was also assumed that the plant would operate 365 days per year. The quantity of straw that would be available for processing in Crop District No. 3 would be approximately 2.7×10^6 lb/day (1.2×10^3 mtons/day). The area of Crop District No. 3 may be divided into two parts, each of which could supply about 1.4×10^6 lb of straw per day (0.6×10^3 mtons of straw per day). The yield of straw could not be expected at this level every year. Therefore, a pyrolysis plant having a capacity of 500 tons (455 mtons) of waste (wet) per day may be considered for installation in each half. This assumption for processing capacity also makes it possible to use the cost of a pyrolysis plant having a capacity of 500 wet tons (455 wet mtons) per day, given in Table 6.1. Data show that the capital cost is U.S. $\$3.82 \times 10^6$ and the operating cost is U.S. $\$5.79$ per wet ton (U.S. $\$6.34$ per wet mton). These values were presented to the Third Mineral Waste Utilization Symposium, held in Chicago, Illinois, in 1972. Based on the assumptions of a 40-year plant life, an interest rate of 10% and 365 operating days per year, the capital cost and operating cost reported in 1972 was projected to a 1975 value of U.S. $\$5.08 \times 10^6$ for capital cost, and U.S. $\$7.78$ per wet ton (U.S. $\$8.56$ per wet mton), or Can. $\$7.70$ per wet ton (Can. $\$8.47$ per wet mton), for operating cost.

The operating cost was estimated from the values given for the pyrolysis of municipal refuse. Municipal waste has a higher moisture

content than straw and pyrolysis costs will therefore vary somewhat. No information on the cost of operating a straw pyrolysis plant was found in the literature. Therefore, the cost data available for the pyrolysis of municipal refuse was applied to a straw pyrolysis plant in this analysis.

The cost of collecting and transporting straw from the field to a central processing site was estimated using a hay stacking and baling system as alternate handling methods. The average hauling distance was taken to be 10 miles. Handling and transportation costs were obtained from the report on "Hay and Forage Harvesting Methods" by Frieson (18) and from direct communications with farmers and companies. Current costs applied to the two handling systems follow:

(i) Hay Stacking System (Hesston StakHand 30A)

(a) value of straw	Can. \$ 2.50 per ton
(b) collecting and stacking	Can. \$ 8.75 per ton
(c) moving stacks a 10-mile distance	Can. \$ <u>2.80</u> per ton
Total	Can. \$ <u>14.05</u> per ton

(ii) Baling System (Mechanical Wagaon 1049)

(a) value of straw	Can. \$ 2.50 per ton
(b) baling and stacking	Can. \$15.00 per ton
(c) loading from a stack to truck or trailer	Can. \$ 2.50 per ton
(d) hauling a 10-mile distance	Can. \$ <u>1.00</u> per ton
Total	Can. \$ <u>21.00</u> per ton

The combined materials handling and processing cost for the Hay Stacking System is Can. \$21.75 per ton (Can. \$23.93 per mton) while that

of the baling system is Can. \$28.70 per ton (Can. \$31.57 per mton).

Products obtained from the results of rice straw pyrolysis carried out by the Bureau of Mines of the United States Department of the Interior are shown in Table 4.1. Data show that yields per ton of feed were 5,981 cu ft (169 cu m) of gas, 11.0 U.S. gallons (42 litres) of oil, 60.3 U.S. gallons (228 litres) of aqueous substances, and 800 lb (0.4 mton) of residue. The heating value of gas produced was 662 Btu/lb (368 kcal/kg) of straw fed. Additional information on this experiment was found in a report on "Energy from the Pyrolysis of Agricultural Wastes" by Schlesinger et al. (58). This report gave the heating value of rice straw, having the moisture content of 7.4%, as 6080 Btu/lb (3,380 kcal/kg) while the heating value of the residue was 7380 Btu/lb (4,100 kcal/kg) of residue. It was also stated that the potential heat available in the products was 94% of the energy in the dry feed material.

From the above information and Table 4.1, the total heat value of the gas produced by pyrolysis together with the residue was 9.9×10^6 Btu/ton (2.7×10^6 kcal/mton) of feed. This quantity of heat is equivalent to 57.1 Imperial gallons (259 litres) of heating oil having a heating value of 19,134 Btu/lb (10,639 kcal/kg) and a current selling price of 33.2 cents per Imperial gallons in Manitoba. The value of the pyrolysis products, excluding oil and aqueous substances, is estimated to be Can. \$18.96 per ton (Can. \$20.86 per mton) of straw.

If the potential heat available in the products of pyrolysis is considered to be 94% of the energy in the dry feed, the total heat available from straw would be 11.3×10^6 Btu/ton (3.1×10^6 kcal/mton) of straw. This quantity of heat is equivalent to 61.3 Imperial gallons (278 litres) of heating oil and has a current value of Can. \$20.35 per

ton (Can. \$22.39 per mton) of straw.

Therefore, the cost-benefit ratio based on the above consideration is as follows:

	<u>Cost-Benefit Ratio</u>	
	<u>Hay Stacking System</u>	<u>Baling System</u>
(a) Based on heat value of gas produced and residue. (excluding oil and aqueous substance)	1:0.87	1:0.66
(b) Based on heat value of 94% of the energy in the dry feed	1:0.94	1:0.71

From the economic considerations related to materials handling and pyrolysis, it is concluded that:

(i) A commercial pyrolysis plant, under present conditions of alternate availability and costs, would not pay its way when the cost of straw collection and transportation to a processing plant are considered.

(ii) Potential energy from the process is competitive with the availability and price of fossil fuels. The economics of the pyrolysis process could change as the availability of alternate energy supplies become more restricted and as the cost for such energy increases.

(iii) Investigation to reduce the high cost of collection, concentration, and transportation of straw together with ways and means of improving the quality and quantity of energy recovery from pyrolysis should be undertaken so that the cost-benefit ratio can be improved.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The discussions in this thesis lead to a number of conclusions.

7.1 Referring to the waste from cereal crop residues, the potential quantity produced annually was estimated and converted to available potential energy as shown in Table 7.1. The table also contains the quantity of annual energy consumption and the comparison percentage between the annual energy consumed and the annual energy available. The values shown are quite attractive but the problem requiring resolution is how to transform these residues into a storable useful energy with high efficiency and at costs competitive with fuels from other available sources.

7.2 Crop residues or other organic solid wastes can be converted biologically or chemically into storable energy. From the review of literature it was found that anaerobic digestion, a biological process, has been practiced in some countries to produce methane gas fuel from farm wastes for the farm use. These countries include India, Taiwan, Germany, France, Australia, and South Africa. Pyrolysis, a chemical process, has also been attempted as a method of converting organic solid wastes to useful energy. Considerable research work has been carried out at the Pittsburgh Energy Research Centre, Bureau of Mines, United States Department of the Interior. No large scale plants for the application of pyrolysis to the conversion of crop residues to energy have been built and operated up to the present time.

7.3 The economics of anaerobic and pyrolysis processes are still in question as their design and operating conditions vary considerably. Local climatic conditions seem to be the most important factor among the parameters affecting anaerobic digestion. The technical problems of both processes are being investigated but the practical problems of materials handling probably represent the greatest problems to be solved. Collection, concentration, transportation, storage, etc., are among those important practical problems. Economics, a problem that is still in question, is the major factor that will determine which sources and processes of energy conversion will be used.

7.4 Experiments on the pyrolysis and anaerobic digestion of oat straw produced results which are shown in Table 7.2. The quantity of gas produced by both processes was low compared to the results at Bureau of Mines. In the pyrolysis experiments conducted by the author, the operating temperature under the pyrolysis reaction was low. Other researchers have found that as the operating temperature is increased there is a corresponding increase in the volume of gas produced. The estimated total heat value of the gas produced in the batch system experiment was less than that of the gas used for heating the pyrolysis tube. This ratio can be improved by increasing the operating temperature and the thermal efficiency of the system. In the anaerobic digestion experiment, the quantity of gas produced was relatively low. However, the results of these two experiments are satisfactory in that they have demonstrated that energy recovery from cereal crop residues is technically feasible using either anaerobic digestion or pyrolysis processes.

7.5 The produced gas from the pyrolysis process contained 25 to 30% CH_4 , 32 to 48% CO_2 while from the anaerobic digestion process it contained 52 to 56% CH_4 , 44 to 48% CO_2 . The remaining components of the gas produced were hydrogen, nitrogen and sometimes traces of hydrogen sulphide or other gases (62). Under the conditions of research work at the United States Department of the Interior, Bureau of Mines, the calorific value of the gas produced in pyrolysis ranges between 450 to 750 Btu/cu ft (4,000 to 6,700 kcal/cu m), depending on the organic material pyrolyzed. The calorific value of gas produced from rice straw was reported to be 662 Btu/cu ft (5,890 kcal/cu m) (58). In India, the gas produced from the bio-gas plant has a calorific value of about 600 Btu/cu ft (5,300 kcal/cu m) (62). In comparison, the calorific value of natural gas which has a methane content of 80% or greater, has a calorific value of 1,000 Btu/cu ft (8,900 kcal/cu m) (62). Bio-gas, even though its calorific value is low, can be burned directly in domestic appliances, as has been demonstrated in Taiwan and India, and processes for the removal of carbon dioxide need not be employed. However, carbon dioxide should be removed to raise the calorific value if the gas is desired as a fuel for internal combustion engines.

7.6 Finally, it is recommended that:

(a) since both pyrolysis and anaerobic digestion processes provide methods for converting cereal crop residues into useful fuel that research should be continued and expanded to further investigate these processes,

(b) a closed thermal system should be developed for further pyrolysis investigation to reduce heat losses and thus increase efficiency,

(c) anaerobic digesters using crop residues as source material should be equipped with an agitator to prevent the collection of residues on liquid surfaces in the digesters, and

(d) concentration of straw in the form of briquets, pellets or other means should be developed to facilitate the development of automatic feeding systems and a continuous-flow process.

TABLE 7.1

Quantity of Residues and Energy Available

Location	Annual cereal crop residues 10^9 lb	Annual energy available 10^{12} Btu (1)	Annual energy consumption 10^{12} Btu (2)	Compared percentage of (1) of (2), %
Canada	99.0	593.4	4,939.5	12.0
Manitoba	12.3	73.7	219.4	33.6
Crop Distric 3	1.9	11.7	*	*
Thailand	48.8	293.4	*	*
*data not available				

TABLE 7.2

Quantity of Gas Produced from Oat Straw

Description	Quantity of gas production cu ft/lb	Remarks
<u>(a) Pyrolysis process</u>		
(a) working temperature at 65-600°F	1.43	(1) pyrolysis of rice straw at the Bureau of Mines at 200-700°C (392-1292°F) Gas yield 5,981 cu ft/ton of straw or about 2.99 cu ft/lb. (Ref. 58)
(b) working temperature at 65-700°F	1.78	
<u>(b) Anaerobic digestion</u>		
(a) batch-feeding basis (95°F)	6.57	(2) Anaerobic digestion of corn straw in India Gas yield 13.0 cu ft/lb of dry matter and 15.0 cu ft/lb of dry matter of straw powder. (Ref 62)
(b) daily-feeding basis (95°F)	6.01	

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APPENDIX A

EQUATION FOR CALCULATING PROPANE GAS SUPPLIED¹

Equation 1

Sizing Factor x Max. Flow Metered Gas (SCFM*) = Max. Flow Air
Equivalent** (SCFM*)

Equation 2

$$\text{Sizing Factor} = \frac{1}{\text{Flow Factor}} = \sqrt{\frac{\rho G_2}{\rho G_1} \times \frac{T_2}{T_1} \times \frac{P_1}{P_2}}$$

ρG_2 = specific gravity of gas to be metered
= 1.56 for propane gas

ρG_1 = specific gravity of air (1.0)

T_2 = absolute operating temperature

T_1 = 530°R or 294°K

P_2 = absolute operating pressure

P_1 = absolute pressure of standard atmosphere

¹Design Specification, Brooks Instrument, Inc., Hatfield, Pennsylvania 19440
*Standard cubic foot per minute at 14.7 psia, 70°F (1.03 kg/sq cm abs, 21°C)

**Max. flow air equivalent (100%) of meter size 2, tube no. R-2-15-C, stainless steel float material, = 16.1 SCFM (7.60 litres/min)

APPENDIX B

ANALYSIS OF GAS PRODUCED BY PYROLYSIS OF STRAW

Four samples of gaseous products were collected by water displacement and analysed by gas chromatography. At least 13 different components were detected. Others may not have eluted from the column under our conditions. Two components, tentatively identified as carbon monoxide and methane, together account for 60 to 80% of the total peak area.

Analysis systems: Gas chromatography; Porapak T, flame ionization detector, automatic integrator for peak area determination. Column temperature was 80°C.

Comments

The flame ionization detector will only detect components which yield ions on combustion; air gases, carbon dioxides, nitrogen oxides, ammonia and water would not show up.

For any one component, the peak area is proportional to the amount of material present. However, the ion yield will differ between components. Thus calculation of composition on the basis of peak area is subject to error. Correct values can only be calculated after all components are identified.

Eight to eleven peaks were found in the various samples. On the basis of retention times, which are characteristic of the components, these peaks represent at least 13 components. Others may be present in amounts too small to be detected and some may not have eluted from the column at the operating temperature.

Positive identification of the various peaks could be done by running the samples through a number of different columns before and after treatment with specific adsorbents and oxidizing agents etc. A quicker route would be the use of combined gas chromatography and Mass Spectrometry. The Chemistry Department (Dr. J.B. Westmore) has an instrument which should do the job.

Notes by Dr. W. Woodbury
Plant Science Department
University of Manitoba
July 18, 1974.

Note: At least some samples should be collected dry since short chain alcohols and aldehydes are quite soluble in water.

APPENDIX B (continued)

Peak Area of Various Components

Retention Time Sec	Sample No.			
	1	2	3	4
4	81	345	287	466
20	-----	-----	-----	52
24	188,331	57,298	677,465	94,216
36	131,563	44,498	422,525	69,149
78	-----	89	-----	-----
89	39,418	11,465	99,183	20,130
99	56,855	18,060	113,616	31,390
140	58	-----	-----	-----
152	-----	-----	3,159	-----
180	1,657	-----	9,670	356
210	23,811	27,842	-----	12,022
255	29,492	9,726	66,879	-----
290	6,057	-----	31,674	1,067
350	7,577	1,391	-----	-----
Total Area	484,900	170,714	1,424,458	250, 023

Components at 24 and 36 seconds are probably carbon monoxide and methane, respectively.
On basis of peak area these two constitute 60 to 80% of total gas detected.

APPENDIX B (continued)

Gas as Percent of Total Peak Area

	Sample No.				Average
	1	2	3	4	
Carbon monoxide	38.8	32.2	47.5	37.6	39.0
Methane	27.1	24.9	29.5	27.6	27.3
Sum (percent of total)	65.9	57.1	77.0	65.2	66.3