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October 1979

Feasibility Study for Anaerobic Digestion of Agricultural Crop Residues

Final Report

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Michael G. Buivid
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Dynatech R/D Company
Cambridge, Massachusetts

MASTER

Prepared Under Subcontract No. XR-9-8157-1
for the

SERI

Solar Energy Research Institute
A Division of Midwest Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

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FOREWORD

This report is the result of a four-month study by Dynatech R/D Co. to assess the economic and technical feasibility of producing methane gas by anaerobic digestion of agricultural crop residues. The intent of the Department of Energy, which financed the preparation of this report, and the Solar Energy Research Institute, which serves as project manager for the anaerobic digestion program, is to use the results of this report to guide the development of program plans and to provide a reasoned analysis of the role this technology might play in future energy supply systems.

The search for economic and renewable energy sources to supply our future national energy needs is at best a complex undertaking, involving many uncertain variables. It is hoped and expected that this report will contribute to an understanding of how the energy available in agricultural crop residues might be developed to help meet those needs.

Dan Jantzen, Project Manager
Biomass Program Office

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ABSTRACT

The objective of this study was to provide cost estimates for the pretreatment/digestion of crop residues to fuel gas. A review of agricultural statistics indicated that the crop residues wheat straw, corn stover, and rice straw are available in sufficient quantity to provide meaningful supplies of gas.

Engineering economic analyses were performed for digestion of wheat straw, corn stover, and rice straw for small farm-, cooperative-, and industrial scales. The small farm scale processed the residue from an average size U.S. farm (400 acres), and the other sizes were two and three orders of magnitude greater.

The results of the analyses indicate that the production of fuel gas from these residues is, at best, economically marginal, unless a credit can be obtained for digester effluent. The use of pretreatment can double the fuel gas output but will not be economically justifiable unless low chemical requirements or low cost chemicals can be utilized. Additional development is necessary in this area. Use of low cost "hole-in-the-ground" batch digestion results in improved economics for the small farm size digestion system, but not for the cooperative and industrial size systems.

Recommendations arising from this study are continued development of autohydrolysis and chemical pretreatment of agricultural crop residues to improve fuel gas yields in an economically feasible manner; development of a low cost controlled landfill batch digestion process for small farm applications; and determination of crop residue digestion by-product values for fertilizer and refeed.

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Section 1
INTRODUCTION

As a result of the energy crisis, a considerable effort has been expended over the last few years to develop alternate renewable sources of energy. One such source is biomass, which can be considered as solar energy being collected and stored by plants. Biomass can be grown specifically for use as an energy crop, or it can be obtained as residues, both from crops and animals. Studies have been undertaken by various organizations under contract with the U.S. Department of Energy (and its predecessor, ERDA) and the Solar Energy Research Institute (SERI) to investigate the feasibility of various biomass sources as potential alternate renewable energy supplies. These include grains and grasses, silviculture, aquatic plants, animal residues, other crops such as corn and sugar cane, and agricultural crop residues.

Once there is an available source of biomass, the next step is to convert the biomass to a more easily utilized form of energy. Both thermochemical and biological processes are being considered as conversion processes for production of liquid and/or gaseous fuels. One such process is the biological anaerobic digestion of biomass for production of methane gas.

This study for SERI has been undertaken to determine cost estimates for fuel gas production by the pretreatment/digestion processing route for three distinct scales of operation, namely a small farm system, a farm cooperative scale system, and a larger scale utility/industrial system. The system of residue cost, pretreatment, digestion, and effluent processing and/or disposal is presented on an economic basis, and the cost of fuel gas is computed. A practical engineering evaluation, economic feasibility study and sensitivity analysis were performed on various systems by including such factors as facility size, processing sequence, chemical requirements, heating requirements, energy and material balances, capital and operating costs, feedstock costs and availability, potential for and value of recovered byproducts, and disposal of effluent streams.

The technical background for conducting this analysis was based on recent work of DOE Fuels from Biomass contractors in which experiments have shown the effects of pretreatment prior to digestion to fuel gas of selected agricultural residues and crop-grown biomass. Pretreatment is defined broadly as the addition of chemicals, or the heating under pressure of the particular biomass, or a combination of these, in order to render the particular biomass more amenable to anaerobic digestion to fuel gas. The economics of pretreatment are presented in this systems analysis, based on the recent experimental results of the aforementioned contractors.

This report is the result of the study to determine cost estimates of fuel gas production from agricultural crop residues via anaerobic digestion. A summary discussion of agricultural statistics indicating crop residue availability, quantity, and composition is presented in Section 2. A review of pretreatment and anaerobic digestion of biomass is presented in Sections 3 and 4. The procedures for economic analyses is given in Section 5. The various base line systems analyses are presented in Section 6, and the sensitivity analysis to show effects of variations of system parameters on unit gas costs is given in Section 7. This study has led to conclusions and recommendations, Section 8, regarding the present and future state-of-the-art of fuel gas production from agricultural crop residues.

Section 2
BIOMASS SOURCES

2.1 Residue Production and Availability

There were approximately 380 million dry tons of crop residues generated on farms in the United States in 1978, including residues remaining in the field after crop harvest, and those taken off the field for concentration at a central location, usually a packing shed. This does not include hay and forage crops which are essentially used entirely for the purpose they are grown, or residues from food processing. The majority of the field residues result from the production of cereals, grain corn and soybeans. At the packing shed vegetable plant materials and hulls from nuts and grains are available in large quantities. Also, accumulated in one area is the cotton "trash" collected by cotton ginning.

The cereal straws (wheat, oats, barley, rye and rice) make up 40% of all crop residues produced in the United States. The residues from grain corn production account for 25% of the total and 22% are from soybean production. Residues concentrated in a central location (peanut, almond, and other hulls; safflowers; sunflowers; and vegetable packing shed residues) represent only 1% of the total residue production, but on a regional basis these residues represent a substantial portion of available biomass and afford the opportunity for establishing a processing plant at the location of accumulation.

Residue production from most crops is expected to increase in the future due primarily to increases in crop production. Projections of crop residue production have been determined by Stanford Research Institute (Ref. 1) based on historical crop production data, 1972 Obers projection data prepared by the U.S. Water Resources Council and information on the quantities of residues generated from each crop. Projections derived from the SRI study for 1980, 1985 and 2020 are presented in Table 2.1. The drop in wheat straw production is a reflection of decreased crop production. It should be noted that some of the major food processing residues have been included in the table. These residues are beyond the scope of this report and are provide for comparison only.

Detailed information on the production of the major residues is presented in Tables 2.3 - 2.11. The tables are based on 1975 crop production data obtained from Agricultural Statistics, 1976, published by U.S.D.A. (Ref.2). Residue production is calculated by using the equation

residue factor = crop production x dry weight factor x residue factor

Dry weight factors and residue factors are listed in Table 2.2.

Wheat, corn and soybeans are the major crops in the United States in terms of magnitude of acreages, total grain yields and total residue yields. These crops constitute the greatest potential biomass from agricultural crops for use as an energy resource. Residues from sorghum and small grains are grown on smaller but still fairly large acreages and constitute a substantial portion of the biomass produced nation-wide. Although the remaining residues are relatively minor when viewed on a nation-wide scale, these crops may be a significant resource on a regional or site specific basis, such as rice straw.

The density of crop residues in the United States is illustrated in Figure 2.1. The most productive farmland and most intensively cultivated area lies in the Corn Belt in the upper Mississippi Valley. In this region, the yield of residues is about 2 tons/ac (0.73 MT/ha), predominantly in the form of cornstalks and soybean stubble. Considerable quantities of wheat and oats are also grown there. In the southeast the major crops are cotton, soybeans and peanuts; and in the southwest, wheat and sorghum. Residue densities are nearer to 1 ton/ac (0.37 MT/ha) in these southern areas.

Further west and north the principal crops in irrigated areas are wheat and corn. All other crops are scattered throughout the United States,

Table 2.1 Projections for U.S. Residue Production from Crops in the Years 1980, 1985, 2000, and 2020. (Derived from Ref. 1)

	1980[c]	1985	2000	2020
	(Thousands Dry Tons)			
Wheat Straw	101,169	85,730	86,659	95,541
Corn Residue	101,023	107,095	142,536	160,142
Soybean Residue	97,754	112,485	158,766	176,408
Grain Sorghum Residue	16,617	19,896	27,482	31,053
Oat Straw	14,950	16,656	17,919	20,295
Barley Straw	13,659	15,607	15,714	17,864
Rice Straw	6,491	5,683	6,813	7,852
Seed Grass Residue	3,709	3,709	3,709	3,709
Vegetable Residues	3,826	3,997	4,648	5,273
Sugarcane Bagasse [a]	3,565	3,842	4,820	6,140
Sugarbeet Residue [b]	3,269	3,494	4,150	5,075
Cotton Residue	2,669	2,898	2,746	3,062
Sugarcane Residue [b]	2,526	2,482	2,820	3,592
Peanut Residue	2,509	2,734	3,451	4,107
Sugarbeet Pulp [a]	2,047	2,187	2,598	3,177
Sunflowers	2,026	2,341	3,325	3,724
Irish Potato Residue	1,970	1,961	2,260	2,532
Rye Straw	1,452	2,001	2,374	2,812
Cotton Gin Trash	1,153	1,371	1,483	1,654
Rice Hulls	1,063	1,023	1,280	1,475
Dry Beans & Peas Residue	656	682	645	661
Almond & Other Hulls & Trash	329	302	335	376
Safflowers	247	285	405	453
Sweet Potato Residue	67	62	53	56
Vegetable Packing Shed Residues (Asparagus, Carrots, Cauliflower, Celery, Sweet Corn)	34	35	38	45

[a] Food processing product

[b] Harvest residue

[c] Calculated by taking average of 1975 historical data and 1985 residue projections presented in Reference 1.

Table 2.2 Factors used for calculations of residue production in Tables 2.3 - 2.11

Table number	Residue	Dry weight factor	Residue factor
2.3	Wheat straw	0.72	2.39
2.4	Corn residue	0.53	1.10
2.5	Soybean field residue	0.85	2.14
2.6	Barley straw	0.91	1.35
2.7	Oat straw	0.90	1.35
2.8	Rye straw	0.72	2.50
2.9	Rice straw	0.80	1.26
2.10	Sorghum residue	0.40	1.57
2.11	Cotton residue	0.50	2.38

Table 2.3 Statistics on Wheat Grain and Wheat Straw Production (1975)

	Area Harvested[a]		Crop Production[a]		Crop Yield Per Harvested Area		Residue Production		Residue Yield Per Harvested Area	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare
New England	0	0	0	0	0	0	0	0	0	0
Mid-Atlantic										
New York	190	77	222	201	1.17	2.61	382	345	2.01	4.48
New Jersey	54	22	58	53	1.08	2.41	100	91	1.85	4.14
Pennsylvania	345	140	341	309	0.99	2.21	587	531	1.70	3.79
EN Central										
Indiana	1,390	563	1,793	1,626	1.29	2.89	3,084	2,797	2.22	4.97
Illinois	1,730	700	2,024	1,836	1.17	2.62	3,481	3,158	2.01	4.51
Michigan	1,020	413	1,163	1,055	1.14	2.55	2,000	1,815	1.96	4.39
Wisconsin	93	38	85	77	0.91	2.03	146	132	1.57	3.47
Ohio	1,770	716	2,230	2,023	1.26	2.83	3,836	3,480	2.17	4.86
WN Central										
Missouri	1,470	595	1,455	1,320	0.99	2.22	2,503	2,270	1.70	3.82
Minnesota	2,867	1,160	2,638	2,393	0.92	2.06	4,537	4,116	1.58	3.55
Iowa	100	40	102	93	1.02	2.33	175	160	1.75	4.00
N. Dakota	10,213	4,133	7,966	7,225	0.78	1.75	13,702	12,427	1.34	3.01
S. Dakota	2,965	1,200	1,868	1,694	0.63	1.41	3,213	2,914	1.08	2.43
Nebraska	3,070	1,242	2,947	2,673	0.96	2.15	5,069	4,598	1.65	3.70
Kansas	12,100	4,897	10,527	9,548	0.87	1.95	18,106	16,422	1.50	3.35

Table 2.3 (Con't.) Statistics on Wheat Grain
Wheat Straw Production (1975)

	Area Harvested[a]		Crop Production[a]		Crop Yield Per Harvested Area		Residue Production		Residue Yield Per Harvested Area	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
South Atlantic										
Delaware	34	14	35	32	1.02	2.29	60	55	1.76	3.93
Maryland	156	63	159	144	1.02	2.29	273	248	1.75	3.94
Virginia	292	118	271	246	0.93	2.08	466	423	1.60	3.58
W. Virginia	17	7	16	15	0.96	2.14	28	26	1.65	3.71
N. Carolina	275	111	256	232	0.93	2.09	440	399	1.60	3.59
S. Carolina	155	63	126	114	0.81	1.81	217	196	1.40	3.11
Georgia	135	55	109	99	0.81	1.80	187	170	1.39	3.09
Florida	20	8	16	15	0.78	1.88	28	26	1.40	3.25
ES Central										
Kentucky	352	142	359	326	1.02	2.30	617	561	1.75	3.95
Tennessee	310	125	288	261	0.93	2.09	495	449	1.60	3.59
Alabama	135	55	97	88	0.72	1.60	167	151	1.24	2.75
Mississippi	185	75	133	121	0.72	1.61	229	208	1.24	2.77
WS Central										
Arkansas	520	210	458	424	0.90	2.02	805	729	1.55	3.47
Louisiana	25	10	12	11	0.48	1.10	21	19	0.84	1.89
Oklahoma	6,700	2,711	4,824	4,375	0.72	1.61	8,297	7,525	1.24	2.78
Texas	5,700	2,307	3,933	3,567	0.69	1.55	6,765	6,135	1.19	2.67
Mountain										
Montana	1,470	595	1,382	1,253	0.94	2.11	2,377	2,155	1.62	3.62
Idaho	1,350	546	1,809	1,641	1.34	3.01	3,111	2,822	2.30	5.17
Wyoming	273	110	205	186	0.75	1.69	353	320	1.29	2.91
Colorado	2,260	915	1,537	1,394	0.68	1.52	2,644	2,398	1.17	2.62
New Mexico	387	157	302	274	0.78	1.75	519	471	1.34	3.00
Arizona	320	130	682	619	2.13	4.76	1,173	1,065	3.67	8.19
Utah	282	114	214	194	0.76	1.70	368	334	1.30	2.93
Nevada	20	8	35	32	1.76	4.00	60	55	3.00	6.88

Table 2.3 (Con't.) Statistics on Wheat Grain and Wheat Straw Production (1975)

	Area Harvested[a]		Crop Production[a]		Crop Yield Per Harvested Area		Residue Production[b]		Residue Yield Per Harvested Area	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
<u>Pacific</u>										
Washington	3,060	1,238	4,345	3,941	1.42	3.18	7,473	6,779	2.44	5.48
Oregon	1,215	492	1,725	1,565	1.42	3.18	5,486	2,692	4.52	5.47
California	1,001	405	1,862	1,689	1.86	4.17	3,203	2,905	3.20	7.17
Alaska	0	0	0	0	0	0	0	0	0	0
Hawaii	0	0	0	0	0	0	0	0	0	0
Total U.S.	69,641	28,183	64,070	58,111	0.92	2.06	110,200	99,951	1.58	3.55

[a] Derived from Agricultural Statistics, 1976, USDA (Ref. 2.2)

[b] Residue production (dry wt) = crop production x dry weight x residue factor

Dry weight factor - 0.72

Residue factor - 2.39

Table 2.4 Statistics on Grain Corn and Corn Residue Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
<u>New England</u>										
<u>Mid-Atlantic</u>										
New York	466	188	1,384	1,255	2.97	6.67	803	728	1.72	3.87
New Jersey	83	33	235	213	2.83	6.45	136	123	1.64	3.73
Pennsylvania	1,080	437	3,100	2,812	2.87	6.43	1,798	1,631	1.66	3.73
<u>EN Central</u>										
Indiana	5,630	2,278	19,311	17,515	3.43	7.69	11,200	10,159	1.99	4.46
Illinois	10,810	4,375	43,889	39,807	4.06	9.10	25,456	23,088	2.35	5.28
Michigan	1,910	773	5,348	4,851	2.80	6.27	3,102	2,813	1.62	3.64
Wisconsin	2,390	967	6,931	6,286	2.90	6.50	4,020	3,646	1.68	3.77
Ohio	3,490	1,412	11,238	10,193	3.22	7.22	6,518	5,912	1.87	4.19
<u>WN Central</u>										
Missouri	2,700	1,093	5,940	5,387	2.20	4.93	3,445	3,124	1.27	2.86
Minnesota	5,820	2,355	14,259	12,933	2.45	5.49	8,270	7,501	1.42	3.18
Iowa	12,300	4,978	38,745	35,142	3.15	7.06	22,472	20,382	1.83	4.09
N. Dakota	132	53	235	213	1.78	4.02	136	123	1.03	2.32
S. Dakota	2,253	910	2,902	2,632	1.29	2.89	1,683	1,526	0.75	1.68
Nebraska	5,920	2,396	17,582	15,947	2.97	6.65	10,197	9,249	1.72	3.86
Kansas	1,640	664	4,822	4,373	2.94	6.58	2,797	2,536	1.70	3.82
<u>South Atlantic</u>										
Delaware	190	77	604	548	3.18	7.12	350	318	1.84	4.13
Maryland	550	222	1,749	1,586	3.18	7.14	1,014	920	1.84	4.14
Virginia	565	229	1,700	1,542	3.01	6.73	986	894	1.74	3.90
W. Virginia	65	26	193	175	2.97	6.73	112	101	1.72	3.88
N. Carolina	1,590	643	3,721	3,375	2.34	5.25	2,158	1,957	1.36	3.04

Table 2.4 (Con't) Statistics on Grain Corn and Corn Residue Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
South Atlantic (continued)										
S. Carolina	550	222	1,210	1,097	2.20	4.94	702	636	1.28	2.86
Georgia	1,880	761	3,610	3,274	1.92	4.30	2,094	1,899	1.11	2.49
Florida	394	159	618	560	1.57	3.52	358	325	0.91	2.04
ES Central										
Kentucky	1,140	461	3,067	2,782	2.69	6.03	1,779	1,613	1.56	3.50
Tennessee	615	249	1,291	1,171	2.10	4.70	749	679	1.22	2.73
Alabama	660	267	1,221	1,107	1.85	4.15	708	642	1.07	2.40
Mississippi	145	59	207	188	1.43	3.19	120	109	0.83	1.85
WS Central										
Arkansas	38	15	66	60	1.75	4.00	38	35	1.00	2.33
Louisiana	60	24	109	99	1.82	4.12	63	57	1.05	2.37
Oklahoma	85	34	238	216	2.80	6.35	138	125	1.62	3.68
Texas	1,100	445	3,960	3,592	3.60	8.07	2,297	2,083	2.09	4.68
Mountain										
Montana	10	4	25	23	2.55	5.75	14	13	1.40	3.25
Idaho	25	10	72	65	2.90	6.50	42	38	1.68	3.80
Wyoming	18	7	50	45	2.80	6.43	29	26	1.61	3.71
Colorado	525	212	1,706	1,547	3.25	7.30	989	897	1.88	4.23
New Mexico	70	28	245	222	3.50	7.93	142	129	2.03	4.61
Arizona	12	5	14	13	1.15	2.60	8	7	0.67	1.40
Utah	15	6	58	53	3.85	8.83	34	31	2.27	5.17
Nevada	0	0	0	0	0	0	0	0	0	0

Table 2.4 (Con't) Statistics on Grain Corn
and Corn residue Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
Pacific										
Washington	34	14	124	112	3.64	8.00	72	65	2.12	4.64
Oregon	11	4	33	30	2.97	7.50	19	17	1.73	4.45
California	254	103	968	878	3.81	8.52	561	509	2.21	4.94
Alaska	0	0	0	0	0	0	0	0	0	0
Hawaii	0	0	0	0	0	0	0	0	0	0
U.S. Total	67,222	27,204	203,010	184,130	3.02	6.77	117,746	106,795	1.75	3.92

[a] Derived from Agricultural Statistics, 1976, USDA (Ref. 2.2)

[b] Residue production (dry wt) = crop production x dry weight x residue factor

Dry weight factor = 0.53
Residue factor = 1.10

Table 2.5 Statistics on Soybean
Field Residue (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
New England	0	0	0	0	0	0	0	0	0	0
Mid-Atlantic										
New York	10	4	7	6	0.72	1.50	13	11	1.30	2.75
New Jersey	79	32	62	56	0.78	1.75	113	102	1.43	3.19
Pennsylvania	43	17	36	33	0.84	1.94	65	60	1.51	3.53
EN Central										
Indiana	3,630	1,469	3,594	3,260	0.99	2.22	6,541	5,933	1.80	4.04
Illinois	8,220	3,326	8,878	8,052	1.18	2.42	16,158	14,655	1.96	4.41
Michigan	610	247	476	432	0.78	1.75	866	786	1.42	3.18
Wisconsin	191	77	145	131	0.76	1.70	264	238	1.38	3.09
Ohio	3,100	1,254	3,069	2,783	0.99	2.22	5,585	5,065	1.80	4.04
WN Central										
Missouri	4,470	1,809	3,487	3,163	0.78	1.75	6,346	5,757	1.42	3.18
Minnesota	3,650	1,477	2,883	2,615	0.79	1.77	5,247	4,759	1.44	3.22
Iowa	6,970	2,821	7,109	6,448	1.02	2.28	12,938	11,735	1.86	4.16
N. Dakota	149	60	86	78	0.58	1.30	156	142	1.05	2.37
S. Dakota	342	138	256	232	0.75	1.68	466	422	1.36	3.06
Nebraska	1,200	486	972	882	0.81	1.81	1,769	1,605	1.47	3.30
Kansas	1,080	437	680	617	0.63	1.41	1,238	1,123	1.15	2.57
South Atlantic										
Delaware	204	82	153	139	0.75	1.69	278	253	1.36	3.08
Maryland	318	129	267	242	0.84	1.87	486	440	1.53	3.41
Virginia	433	175	325	295	0.75	1.68	591	537	1.36	3.07
W. Virginia	0	0	0	0	0	0	0	0	0	0
N. Carolina	1,420	575	994	901	0.70	1.57	1,809	1,640	1.27	2.85

Table 2.5 (Con't) Statistics on Soybean Field Reisdue (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
South Atlantic (continued)										
S. Carolina	1,380	558	911	826	0.66	1.48	1,658	1,503	1.20	2.69
Georgia	1,260	510	958	869	0.76	1.70	1,743	1,581	1.38	3.10
Florida	295	119	212	192	0.72	1.61	386	349	1.31	2.93
ES Central										
Kentucky	1,200	486	972	882	0.81	1.81	1,769	1,605	1.47	3.30
Tennessee	1,850	749	1,387	1,258	0.75	1.68	2,524	2,289	1.36	3.06
Alabama	1,310	530	956	867	0.73	1.63	1,740	1,578	1.33	2.98
Mississippi	3,120	1,263	2,090	1,896	0.67	1.50	3,304	1,631	1.22	1.29
WS Central										
Arkansas	4,700	1,902	3,431	3,112	0.73	1.64	6,244	5,664	1.33	2.98
Louisiana	1,920	777	1,402	1,272	0.73	1.64	2,552	2,315	1.33	2.98
Oklahoma	237	96	163	148	0.69	1.54	297	269	1.25	2.80
Texas	370	149	277	251	0.75	1.68	504	457	1.36	3.07
Mountain	0	0	0	0	0	0	0	0	0	0
Pacific	0	0	0	0	0	0	0	0	0	0
U.S. Total	53,761	21,757	46,449	42,129	0.86	1.94	84,537	76,675	1.57	3.52

Table 2.6 Statistics on Barley Grain and Barley Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare
New England	0	0	0	0	0	0	0	0	0	0
Mid-Atlantic										
New York	12	5	12	11	1.00	2.20	15	13	1.25	2.60
New Jersey	18	7	22	20	1.25	2.86	27	25	1.50	3.57
Pennsylvania	155	63	186	169	1.20	2.68	229	208	1.47	3.30
EN Central										
Indiana	10	4	10	9	1.00	2.25	12	11	1.20	2.75
Illinois	14	6	14	13	1.00	2.17	17	16	11.38	2.67
Michigan	22	9	25	23	1.15	2.55	31	28	1.41	3.11
Wisconsin	35	14	36	33	1.03	2.36	44	40	1.26	2.86
Ohio	12	5	13	12	1.13	2.40	16	15	1.33	3.00
WN Central										
Missouri	11	4	9	8	0.86	2.00	11	10	1.00	2.50
Minnesota	850	344	765	694	0.90	2.02	941	854	1.11	2.48
Iowa	0	0	0	0	0	0	0	0	0	0
N. Dakota	2,100	850	1,911	1,733	0.91	2.04	2,350	2,131	1.12	2.51
S. Dakota	532	215	394	357	0.74	1.66	485	439	.91	2.04
Nebraska	33	13	28	25	0.86	1.92	34	31	1.03	2.38
Kansas	55	22	46	42	0.84	1.91	56	52	1.02	2.36
South Atlantic										
Delaware	23	9	22	20	0.98	2.22	27	25	1.17	2.78
Maryland	100	40	103	93	1.03	2.32	127	114	1.27	2.85
Virginia	104	42	117	106	1.13	2.52	144	130	1.38	3.09
W. Virginia	10	4	11	10	1.10	2.50	13	12	1.30	3.00
N. Carolina	57	23	61	55	1.08	2.39	75	68	1.32	2.96

Table 2.6 (Con't) Statistics on Barley Grain and Barley Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
South Atlantic (continued)										
S. Carolina	23	9	21	19	0.91	2.11	26	23	1.13	2.55
Georgia	8	3	7	6	0.91	2.00	9	7	1.12	2.33
Florida	0	0	0	0	0	0	0	0	0	0
ES Central										
Kentucky	34	14	30	27	0.88	1.93	37	33	1.09	2.36
Tennessee	14	6	10	9	0.74	1.50	12	11	0.86	1.83
Alabama	0	0	0	0	0	0	0	0	0	0
Mississippi	0	0	0	0	0	0	0	0	0	0
WS Central										
Arkansas	0	0	0	0	0	0	0	0	0	0
Louiana	0	0	0	0	0	0	0	0	0	0
Oklahoma	93	38	67	61	0.72	1.60	82	75	0.88	1.97
Texas	70	28	57	52	0.82	1.86	70	64	1.00	2.28
Mountain										
Montana	1,300	526	1,222	1,108	0.94	2.17	1,503	1,363	1.16	2.59
Idaho	755	305	981	890	1.20	2.92	1,207	1,095	1.60	3.59
Wyoming	134	54	183	166	1.37	3.07	255	204	1.90	3.78
Colorado	230	93	292	265	1.27	2.85	359	326	1.56	3.50
New Mexico	28	11	39	35	1.39	3.18	48	43	1.71	3.91
Arizona	115	46	207	183	1.80	4.09	255	231	2.22	5.02
Utah	135	55	194	176	1.44	3.20	239	216	1.60	3.93
Nevada	14	6	17	15	1.20	2.50	21	18	1.50	3.00

Table 2.6 (Con't) Statistics on Barley Grain and Barley Straw Producton (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
Pacific										
Washington	400	162	508	461	1.27	2.84	625	567	1.56	3.50
Oregon	177	72	212	192	1.20	2.67	261	236	1.47	3.28
California	1,060	429	1,452	1,317	1.37	3.07	1,786	1,620	1.68	3.78
Alaska	0	0	0	0	0	0	0	0	0	0
Hawaii	0	0	0	0	0	0	0	0	0	0
Total U.S.	8,743	3,538	9,180	8,326	1.05	2.35	11,291	10,241	1.29	2.89

[a] Derived from Agricultural Statistics, 1976, USDA (Ref. 2.2)

[b] Residue production (dry wt) = dry weight x residue factor

Dry weight factor = 0.91

Residue factor = 1.35

Table 2.7 Statistics on Oat Grain and Oat Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectares
<u>New England</u>										
Maine	42	17	36	33	.86	1.94	44	40	1.05	2.35
<u>Mid-Atlantic</u>										
New York	350	142	313	288	0.91	2.03	388	351	1.11	2.47
New Jersey	7	3	5	4	0.69	.33	6	5	0.86	1.67
Pennsylvania	375	152	307	278	0.82	1.83	374	339	1.00	2.23
<u>EN Central</u>										
Indiana	250	101	207	188	0.83	1.86	252	229	1.01	2.27
Illinois	490	198	421	382	0.86	1.93	514	466	1.05	2.35
Michigan	370	150	333	302	0.90	2.01	406	368	1.10	2.45
Wisconsin	1,350	546	1,183	1,077	0.88	1.97	1,449	1,314	1.07	2.41
Ohio	500	202	490	444	0.98	2.20	598	542	1.20	2.68
<u>WN Central</u>										
Missouri	100	40	62	56	0.62	1.40	76	68	0.76	1.70
Minnesota	2,000	809	1,620	1,469	0.81	1.81	1.976	1,792	0.99	2.21
Iowa	1,500	607	1,275	1,156	0.85	1.90	1.555	1,410	1.04	2.32
N. Dakota	1,370	554	904	820	0.66	1.48	1.103	1,000	0.80	1.80
S. Dakota	2,230	902	1,561	1,416	0.70	1.57	1,904	1,727	0.85	1.91
Nebraska	590	239	460	417	0.78	1.74	561	509	0.95	2.13
Kansas	150	61	96	87	0.64	1.43	117	106	0.78	1.74
<u>South Atlantic</u>										
Delaware	0	0	0	0	0	0	0	0	0	0
Maryland	24	10	21	19	0.88	1.90	26	23	1.08	2.30
Virginia	40	16	27	24	0.67	1.50	33	29	0.82	1.81
W. Virginia	18	7	12	11	0.69	1.57	15	13	0.83	1.86
N. Carolina	80	32	64	58	0.80	1.81	73	71	0.97	2.22

Table 2.7 (Con't) Statistics on Oat Grain and Oat Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare
South Atlantic (continued)										
S. Carolina	73	29	51	46	0.70	1.59	62	56	0.85	1.93
Georgia	90	36	65	59	0.72	1.64	79	72	0.88	2.00
Florida	12	5	8	7	0.66	1.40	10	8	0.67	1.60
ES Central										
Kentucky	10	4	7	6	0.66	1.50	8	7	0.80	1.75
Tennessee	30	12	19	17	0.64	1.42	23	21	0.77	1.75
Alabama	33	13	18	16	0.54	1.23	22	19	0.67	1.46
Mississippi	27	11	17	15	0.64	1.36	21	18	0.78	1.64
WS Central										
Arkansas	60	24	48	43	0.80	1.79	58	52	0.97	2.17
Louisiana	8	3	4	4	0.53	1.33	5	5	0.62	1.67
Oklahoma	120	48	64	58	0.53	1.21	78	71	0.65	1.46
Texas	650	263	312	283	0.48	1.08	381	345	0.59	1.31
Mountain										
Montana	250	101	170	154	0.68	1.52	207	188	0.83	1.86
Idaho	64	26	55	50	0.86	1.92	67	61	1.05	2.35
Wyoming	50	20	32	29	0.64	1.45	39	35	0.78	1.75
Colorado	42	17	31	28	0.75	1.65	38	34	0.90	2.00
New Mexico	0	0	0	0	0	0	0	0	0	0
Arizona	0	0	0	0	0	0	0	0	0	0
Utah	13	5	12	11	0.90	2.20	15	13	1.15	2.60
Nevada	3	1	3	3	0.88	3.00	4	4	1.33	4.00

Table 2.7 (Con't) Statistics On Oat Grain and Oat Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
Pacific										
Washington	45	18	37	33	0.83	1.83	45	40	1.00	2.22
Oregon	80	32	64	58	0.80	1.81	78	71	0.97	2.22
California	113	46	96	87	0.85	1.89	117	106	1.03	2.30
Alaska	0	0	0	0	0	0	0	0	0	0
Hawaii	0	0	0	0	0	0	0	0	0	0
Total U.S.	13,609	5,507	10,479	9,504	0.77	1.72	12,784	11,595	0.94	2.10

[a] Derived from Agricultural Statistics, 1976, USDA (Ref. 2.2

[b] Residue production (dry wt.) = crop production x dry weight x residue factor

Dry weight factor = 0.90

Residue factor = 1.35

Table 2.8 Statistics on Rye Grain and
Rye Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare
New England	0	0	0	0	0	0	0	0	0	0
Mid-Atlantic										
New York	12	5	10	9	0.84	1.80	18	16	1.50	3.20
New Jersey	7	3	5	4	0.70	1.33	9	7	1.28	2.33
Pennsylvania	16	6	13	12	0.81	2.00	23	22	1.44	3.67
EN Central										
Indiana	9	4	6	4	0.73	1.00	11	7	1.22	1.75
Illinois	17	7	10	9	0.62	1.28	18	16	1.06	2.28
Michigan	25	10	17	12	0.70	1.20	31	22	1.24	2.20
Wisconsin	15	6	9	5	0.59	0.83	16	9	1.07	1.50
Ohio	7	3	5	4	0.78	1.33	9	7	1.28	2.33
WN Central										
Missouri	11	4	7	6	0.62	1.50	13	11	1.18	2.75
Minnesota	89	36	62	56	0.70	1.55	112	101	1.26	2.80
Iowa	5	2	3	3	0.67	1.50	5	5	1.00	2.50
N. Dakota	119	48	83	75	0.70	1.56	149	135	1.25	2.81
S. Dakota	102	41	65	42	0.64	1.02	117	76	1.15	1.85
Nebraska	55	22	31	28	0.56	1.27	56	50	1.02	2.27
Kansas	15	6	9	8	0.59	1.33	16	14	1.07	2.33
South Atlantic										
Delaware	9	7	5	4	0.62	0.57	9	7	1.00	1.00
Maryland	11	4	8	7	0.73	1.75	14	13	1.27	3.25
Virginia	14	6	9	8	0.64	1.33	16	14	1.14	2.33
W. Virginia	0	0	0	0	0	0	0	0	0	0
N. Carolina	20	8	10	9	0.50	1.12	18	16	0.90	2.00

Table 2.8 (Con't) Statistics on Rye Grain and Rye Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
South Atlantic (continued)										
S. Carolina	33	13	16	14	0.50	1.08	29	25	0.88	1.92
Georgia	105	42	44	40	0.42	0.95	79	72	0.75	1.71
Florida	0	0	0	0	0	0	0	0	0	0
ES Central										
Kentucky	4	2	3	3	0.70	1.50	5	5	1.25	2.50
Tennessee	2	1	1	1	0.48	1	2	2	1.00	2.00
Alabama	0	0	0	0	0	0	0	0	0	0
Mississippi	0	0	0	0	0	0	0	0	0	0
WS Central										
Arkansas	0	0	0	0	0	0	0	0	0	0
Louisiana	0	0	0	0	0	0	0	0	0	0
Oklahoma	36	14	19	13	0.53	0.93	34	23	0.94	1.64
Texas	40	16	21	19	0.53	1.19	38	34	0.85	2.12
Mountain										
Montana	0	0	0	0	0	0	0	0	0	0
Idaho	0	0	0	0	0	0	0	0	0	0
Wyoming	8	3	5	4	0.62	1.33	9	7	1.12	2.33
Colorado	22	9	2	2	0.11	0.22	4	4	0.18	0.44
New Mexico	0	0	0	0	0	0	0	0	0	0
Arizona	0	0	0	0	0	0	0	0	0	0
Utah	0	0	0	0	0	0	0	0	0	0
Nevada	0	0	0	0	0	0	0	0	0	0

Table 2.8 (Con't) Statistics On Rye Grain and Rye Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
<u>Pacific</u>										
Washington	10	4	7	6	0.73	1.50	13	11	1.30	2.75
Oregon	11	4	8	7	0.76	1.75	14	13	1.27	3.25
California	0	0	0	0	0	0	0	0	0	0
Alaska	0	0	0	0	0	0	0	0	0	0
Hawaii	0	0	0	0	0	0	0	0	0	0
Total U.S.	814	329	505	458	.62	1.39	909	824	1.12	2.50

[a] Derived from <u>Agriculatural Statistics</u>, 1976, USDA (Ref. 2.2)

[b] Residue production (dry wt) = crop production x dry weight x residue factor

Dry weight factor = 0.72

Residue factor = 2.50

Table 2.9 Statistics on Rice Grain and Rice Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
New England	0	0	0	0	0	0	0	0	0	0
Mid-Atlantic	0	0	0	0	0	0	0	0	0	0
EN Central	0	0	0	0	0	0	0	0	0	0
WN Central	0	0	0	0	0	0	0	0	0	0
Missouri	18	7	37	33	2.10	4.71	37	33	2.05	4.71
South Atlantic										
ES Central										
Mississippi	171	69	333	302	1.95	4.38	336	305	1.96	4.42
WS Central										
Arkansas	882	357	2,002	1,816	2.27	5.09	2,022	1,834	2.29	5.14
Louisiana	658	266	1,250	1,134	1.90	4 26	1,262	1,145	1.92	4.30
Oklahoma	0	0	0	0	0	0	0	0	0	0
Texas	548	222	1,249	1,133	2.28	5.10	1,261	1,144	2.30	5.15
Mountain	0	0	0	0	0	0	0	0	0	0
Pacific										
California	525	212	1,522	1,380	2.90	6.50	1,537	1,394	2.93	6.57
U.S. Total	2,802	1,134	6,383	5,794	2.28	5.11	6,459	5,852	2.30	5.16

Table 2.10 Statistics on Grain Sorghum and Sorghum Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Reside Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
New England	0	0	0	0	0	0	0	0	0	0
Mid-Atlantic	0	0	0	0	0	0	0	0	0	0
EN Central										
Indiana	18	7	32	29	1.79	4.14	20	18	1.11	2.57
Illinois	60	24	114	103	1.90	4.29	72	65	1.20	2.71
Michigan	0	0	0	0	0	0	0	0	0	0
Wisonsin	0	0	0	0	0	0	0	0	0	0
Ohio	0	0	0	0	0	0	0	0	0	0
WN Central										
Missouri	490	198	740	671	1.51	3.39	466	423	0.95	2.14
Minnesota	0	0	0	0	0	0	0	0	0	0
Iowa	26	10	45	41	1.79	4.10	28	26	1.08	2.60
N. Dakota	0	0	0	0	0	0	0	0	0	0
S. Dakota	247	100	180	163	0.73	1.63	113	103	0.46	1.03
Nebraska	1,900	767	2,926	2,654	1.54	3.46	1,843	1,672	0.97	2.18
Kansas	3,430	1,388	4,047	3,671	1.18	2.64	2,550	2,313	0.74	1.67
South Atlantic										
Delaware	0	0	0	0	0	0	0	0	0	0
Maryland	0	0	0	0	0	0	0	0	0	0
Virginia	14	6	14	13	0.98	2.17	9	8	0.64	1.33
W. Virginia	0	0	0	0	0	0	0	0	0	0
N. Carolina	85	34	121	108	1.43	3.18	76	68	0.89	2.00

Table 2.10 (Con't) Statistics On Grain Sorghum and Sorghum Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
South Atlantic (continued)										
S. Carolina	17	7	17	15	0.98	2.14	11	9	0.65	1.28
Georgia	47	19	47	43	1.01	2.26	30	27	0.64	1.42
Florida	0	0	0	0	0	0	0	0	0	0
ES Central										
Kentucky	21	8	33	34	1.82	4.25	24	21	1.14	2.62
Tennessee	26	10	35	32	1.34	3.20	22	20	0.85	2.00
Alabama	40	16	33	34	0.95	2.12	24	21	0.60	1.31
Mississippi	38	15	37	33	0.98	2.20	23	21	0.60	1.40
WS Central										
Arkansas	200	81	274	248	1.37	3.06	173	156	0.86	1.92
Louisiana	28	11	25	23	0.92	2.09	16	14	0.57	1.27
Oklahoma	660	267	670	608	1.06	2.28	422	383	0.64	1.43
Texas	7,200	2,914	10,512	9,534	1.46	3.27	6,622	6,006	0.92	2.06
Mountain										
Montana	0	0	0	0	0	0	0	0	0	0
Idaho	0	0	0	0	0	0	0	0	0	0
Wyoming	0	0	0	0	0	0	0	0	0	0
Colorado	290	117	212	192	0.73	1.64	133	121	0.46	1.03
New Mexico	310	125	434	394	1.40	3.15	273	248	0.88	1.98
Arizona	165	67	313	284	1.90	4.23	197	180	1.19	2.64
Utah	0	0	0	0	0	0	0	0	0	0
Nevada	0	0	0	0	0	0	0	0	0	0

Table 2.10 (Con't) Statistics on Grain Sorghum and Sorghum Straw Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
Pacific										
Washington	0	0	0	0	0	0	0	0	0	0
Oregon	0	0	0	0	0	0	0	0	0	0
California	207	84	418	379	2.02	4.51	263	239	1.27	2.84
Alaska	0	0	0	0	0	0	0	0	0	0
Hawaii	0	0	0	0	0	0	0	0	0	0
Total U.S.	15,519	6,280	21,261	19,284	1.37	3.07	13,394	12,149	0.86	1.93

[a] Derived from Agricultural Statistic, 1976, USDA (Ref. 2.2)

[b] Residue production (dry wt.) = crop production x dry weight x residue factor

Dry weight factor = 0.40
Residue factor = 1.57

Table 2.11 Statistics on Cotton and Cotton Residue Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
New England	0	0	0	0	0	0	0	0	0	0
Mid-Atlantic	0	0	0	0	0	0	0	0	0	0
EN Central	0	0	0	0	0	0	0	0	0	0
WN Central										
Missouri	210	85	46	41	.22	.48	55	49	.26	.58
South Atlantic										
Virginia	1	0	0.2	0.2	.17	0	0	0	0	0
N. Carolina	53	21	11	10	.21	.48	13	12	.24	.57
S. Carolina	103	42	24	22	.23	.52	28	26	.27	.62
Georgia	160	65	35	32	.22	.49	42	38	.26	.58
Florida	4	2	0.7	0.6	.17	.30	1	1	.25	.50
ES Central										
Kentucky	1	0	0.1	0.1	.13	0	0	0	0	0
Tennessee	315	127	53	48	.17	.38	63	57	.20	.45
Alabama	370	150	74	67	.20	.45	88	80	.24	.53
Mississippi	1,100	445	253	229	.23	.51	301	272	.27	.61
WS Central										
Arkansas	680	275	163	148	.24	.54	194	176	.28	.64
Louisiana	310	125	84	76	.27	.61	100	90	.32	.72
Oklahoma	295	119	41	37	.14	.31	49	44	.17	.37
Texas	3,924	1,588	785	712	.20	.45	934	847	.24	.53

Table 2.11 (Con't) Statistics on Cotton and Cotton Residue Production (1975)

	Area Harvested[a]		Crop Production[a] (wet wt)		Crop Yield Per Harvested Area (wet wt)		Residue Production[b] (dry wt)		Residue Yield Per Harvested Area (dry wt)	
	1000 acres	1000 hectares	1000 tons	1000 Metric tons	tons/acre	MT/hectare	1000 tons	1000 Metric tons	tons/acre	MT/hectare
Mountain										
New Mexico	98	40	19	17	.19	.42	23	20	.23	.50
Arizona	298	120	152	138	.51	1.15	181	164	.61	1.37
Nevada	1	0	0.4	.3	.36	0	0	0	0	0
Pacific										
California	875	354	472	428	.54	1.21	562	509	.64	1.44
U.S. Total	8,796	3,560	2,023	1,835	.23	.51	2,407	2,184	.27	.61

[a] Derived from Agricultural Statistics, 1976, USDA (Ref. 2.2)

[b] Residue production (dry wt) = crop production x dry weight x residue factor

Dry weight factor = 0.50

Residue factor = 2.38

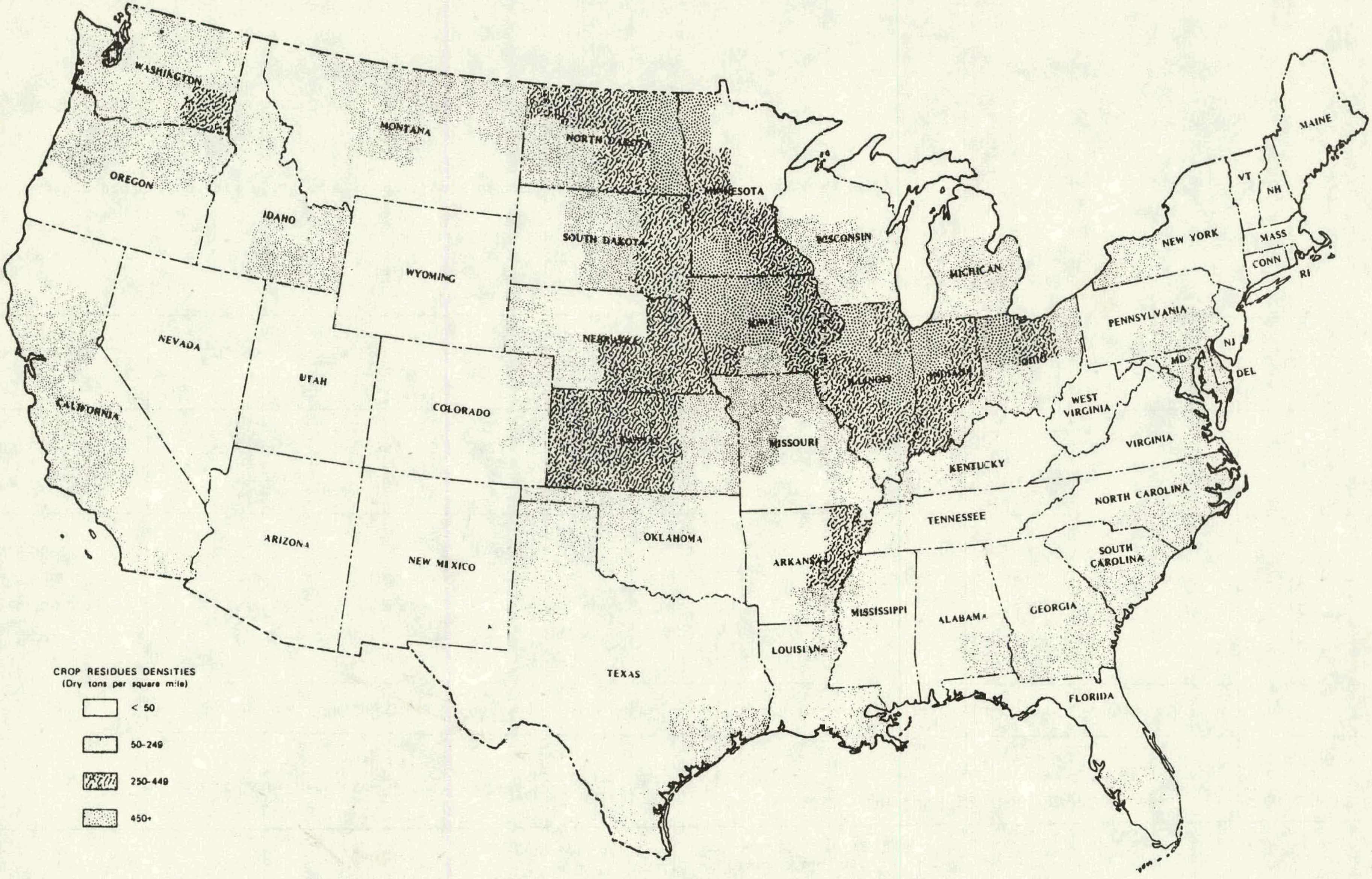

Figure 2.1

Density of Crop Residues in the United States their locations dictated by regional climatic conditions.

Farm Acreage

There is considerable variation in the size of farms in different regions of the United States. Farm size and major crops produced are shown in Table 2.12 according to state and region. Along the east coast and in most of the central regions farms are relatively small averaging about 200 acres per farm. Along the west coast farms are more like 500-600 acres per farm. The largest farms are found in the mountain region and the west north central region where farm acreage is in the thousands. The average farm size for the total United States in 1977 was 393 acres/farm.

Availability of Crop Residues

Not all residues produced in the United States are available for utilization as an energy resource. A national inventory of crop residues in the field and at packing sheds (Ref.4) indicated that of the 322 million dry tons of crop residue produced in the U.S. in 1975, 278 million are considered available for utilization. The availability of the residues depends on the efficiency of collection methods, seasonality of the crop and competition with other uses for the residue.

Based on current technology and the efficiency of methods to collect residues, the harvestability of individual crop residues has been reported (Ref. 5). As shown in Table 2.13 only about 75% of most residues is considered collectable.

The continuity of supply of crop residues is an important consideration for evaluation of this biomass as an energy resource. Crop residue production depends heavily on season resulting in a discontinuity of supply and the necessity to either store the residue or to use large quantities immediately after harvest and sustain long periods of zero production. According to the residue inventory (Ref. 4), 8% of the crop residues are generated in the first quarter of the year, 12% in the second quarter, 42% in the third quarter and

Table 2.12 Farm size and major crops generating residues in the United States

State	Major Crop Residues Available	Farm Size [a]							
		Average Acre/Farm (1977)	# Farms within Acreage Range (1974)						
			1-49	50-99	100-199	200-499	500-999	1000-1999	2000-over
New England									
Maine	Oat straw, vegetable residues	225	1,440	1,117	951	435	43	11	3
New Hampshire	Vegetable residues	215	540	391	253	89	5	0	0
Vermont	Vegetable residues	282	1,015	1,367	1,374	547	38	5	0
Massachusetts	Vegetable residues	125	1,742	626	358	119	14	4	1
Rhode Island	Vegetable residues	96	228	79	37	17	2	0	0
Connecticut	Vegetable residues	121	1,157	484	316	148	11	2	0
Mid-Atlantic									
New York	Wheat straw, corn residues, oat straw	196	8,238	8,542	8,856	4,664	591	97	11
New Jersey	Wheat straw, corn residues, oat straw	130	2,450	1,091	799	527	136	22	3
Pennsylvania	Wheat straw, corn residues, oat straw	139	11,844	11,967	8,453	3,363	310	47	11
EN Central									
Indiana	Corn & soybean residues, oat straw	170	19,575	16,082	14,113	13,751	3,531	521	50
Illinois	Corn & soybean residues, wheat straw	242	14,485	16,272	23,313	30,408	8,106	1,046	102
Michigan	Corn residue, wheat straw	158	13,503	13,081	10,287	7,072	1,279	193	23
Wisconsin	Corn residue, oat straw	191	14,786	23,185	23,562	9,995	827	148	44
Ohio	Corn & soybean residues, wheat straw	150	20,792	18,131	14,699	11,395	2,311	351	25
WN Central									
Missouri	Corn & soybean residues, wheat straw	238	22,671	17,792	15,544	12,974	3,353	718	81
Minnesota	Corn & soybean residues, wheat straw	262	9,444	16,921	26,337	23,915	4,969	1,055	183
Iowa	Corn & soybean residues, oat straw	580	12,788	18,959	35,100	38,103	5,927	631	54
N. Dakota	Wheat, barley, & oat straws	1,040	826	2,055	5,600	16,588	11,189	2,927	419
S. Dakota	Wheat straw, corn residue, oat straw	1,083	1,595	2,748	7,198	16,240	7,321	1,769	301
Nebraska	Corn & sorghum residues, wheat straw	706	4,261	7,369	15,308	23,601	5,928	1,095	210
Kansas	Wheat straw, corn & sorghum residues	636	7,454	10,331	14,284	21,184	8,606	2,368	373
South Atlantic									
Delaware	Corn & soybean residues, wheat straw	197	838	538	470	396	154	51	9
Maryland	Corn & soybean residues	166	4,294	2,236	2,048	1,437	342	110	21
Virginia	Corn residue, peanut hay	153	18,406	5,369	3,204	2,037	456	86	5
W. Virginia	Corn residue	179	3,259	1,465	664	206	29	3	0
N. Carolina	Corn & soybean residues, peanut hay	109	40,032	9,632	5,566	3,155	651	172	21
S. Carolina	Corn & soybean residues, peanut hay	166	8,327	3,237	2,112	1,780	598	247	55
Georgia	Corn & soybean residues, peanut hay	243	12,976	6,534	4,336	3,803	1,178	368	57
Florida	Sugarcane residues	431	10,457	2,721	1,385	1,330	417	196	130

Table 2.12 (Continued)

State	Major Crop Residues Available	Average Acre/Farm (1977)	Farm Size[a] # Farms within Acreage Range (1974) 1-49	50-99	100-199	200-499	500-999	1000-1999	2000-over
ES Central									
Kentucky	Corn & soybean residues	129	47,640	9,731	4,680	2,442	573	143	18
Tennessee	Corn & soybean residues	124	29,219	7,568	3,953	2,605	758	268	45
Alabama	Corn & soybean residues, cotton trash, peanut hay	188	12,852	4,423	3,008	2,346	721	201	36
Mississippi	Soybean residue, cotton trash, rice straw	205	11,000	3,982	2,547	2,508	1,385	794	280
WS Central									
Arkansas	Soybean residue, rice straw, cotton trash	258	10,271	4,176	3,047	3,827	2,419	1,127	358
Louisiana	Soybean & sugarcane residues, rice straw, cotton trash	259	6,209	2,669	2,245	2,749	1,382	509	126
Oklahoma	Wheat straw, peanut hay, sorghum residue	428	9,112	7,702	8,074	9,135	3,719	929	119
Texas	Sorghum & corn residues, cotton trash, wheat straw	124	26,342	14,291	13,354	15,404	7,212	2,553	579
Mountain									
Montana	Soybean & corn residues, wheat straw	2,678	1,539	2,157	3,535	5,600	3,691	1,587	400
Idaho	Wheat & barley straws	580	4,295	3,857	4,109	3,573	1,408	614	193
Whoming	Wheat & barley straws, sugarbeat residue	4,481	643	945	1,554	1,755	588	199	48
Colorado	Sorghum residue, wheat straw, cotton trash	1,362	3,057	2,894	4,093	4,800	2,402	829	259
New Mexico	Sorghum residue, wheat straw, cotton trash	4,026	1,500	769	817	879	335	117	22
Arizona	Cotton trash, wheat straw	6,643	997	376	361	488	345	169	85
Utah	Wheat & barley straws, sugarbeet residue	1,032	2,893	2,067	1,576	1,036	206	89	11
Nevada	Wheat straw	4,500	266	238	318	324	131	68	35
Pacific									
Washington	Wheat straw	415	8,009	2,770	2,415	2,801	1,785	878	268
Oregon	Wheat straw	600	6,328	2,667	2,205	2,121	996	437	162
California	Rice straw, vegetable residues, cotton trash	552	22,902	6,380	4,867	4,138	1,977	1,071	556
Alaska	Few available	5,700	86	37	22	17	1	1	1
Hawaii	Sugarcane residues	535	1,563	35	15	7	2	1	23
U.S. TOTAL	Corn & soybean residues, wheat straw	393	476,096	300,056	314,862	317,834	100,358	26,827	5,816

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[a] From Reference 3

Table 2.13. Percentage of Aerial Residues Considered Harvestible for Biomass Using Present Technology. (Reference 5)

Residue	%Harvestability
Wheat straw	75
Corn residue	75
Soybean residue	50
Grain sorghum residue	85
Oat straw	75
Barley straw	75
Rye straw	75
Rice straw	90
Seed grass residue	100
Peanut hay	100
Sunflowers	85
Safflowers	75

38% in the fourth quarter. The seasonality of residue availability is reflected in variations in harvest schedules of crops grown in the Imperial Valley as illustrated in Figure 2.2.

Currently 75% of the residues produced in the United States are returned to the soil for the purpose of fertilizing and conditioning the soil and as a disposal method. This includes most of the herbaceous high moisture residues. Only about 20% of the residues such as corn straw, sorghum residues and almond hulls are used in other ways, primarily as feed for cattle. Small quantities are used as bedding for animals and for making fiberboard. The remaining 5% are burned or landfilled at a cost. This includes rice straw and other grain straws, vegetable packing shed residues, cotton ginning wastes and some nut hulls.

Plowing residues under the soil following harvest has proved to be an effective method to control erosion, condition the soil for greater absorbance and to provide organic nutrients for utilization by future crops. The impact that continuous removal of the aerial residues will have still remains to be thoroughly examined. This effect should be a major factor in the determination of availability of agricultural biomass sources.

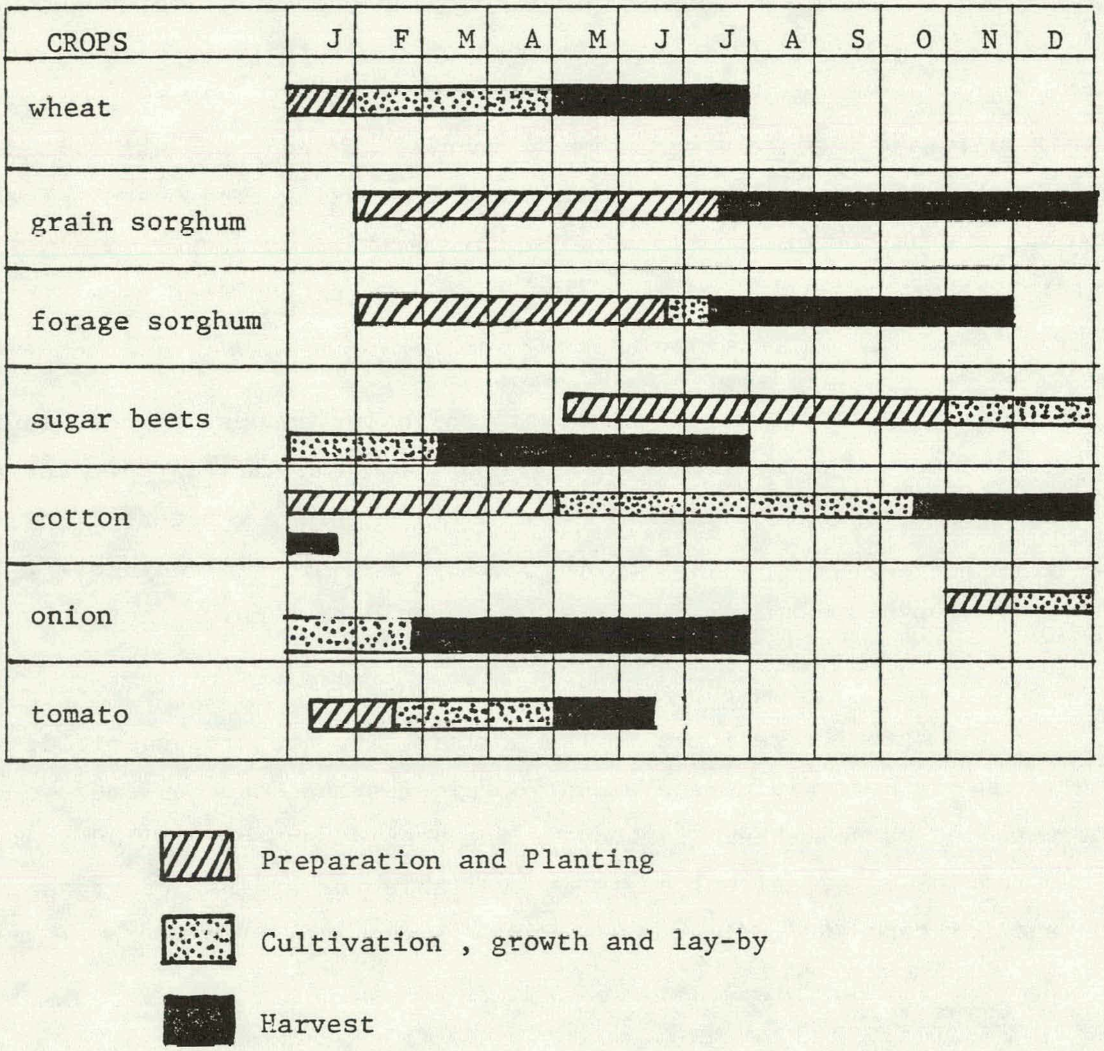
The need for residues in the soil is site and crop specific, and guidelines for determining the amount of biomass that can be removed have not yet been established. A study of the problem and a detailed analysis of residue removal on a regional basis is available for grains and grasses (Ref. 5) and for corn (Ref. 7).

2.2 Feed Composition

The composition of the feedstock determines the availability of components to the bacteria during digestion and consequently influences the rate at which the conversion to methane and carbon dioxide takes place. Not only will the bacterial population vary in composition with the composition of the feedstock input to digesters, but the relative concentrations of the different groups of bacteria would be expected to vary with the concentration

Figure 2.2

Schedule of Planting and Harvest of Crops in the Imperial Valley, California (Ref. 6)



of feedstock added.

Digestion pathways for the major feedstock components are shown in Figure 2.3. Carbohydrates, protein and lipids are the essential components for hydrolysis and fermentation to produce methane . Macronutrients must also be available in the feedstock or added for digestion by microorganisms to take place. The components of agricultural residues as reported in the literature are shown in Table 2.14.

Carbohydrates

The largest constituent of carbohydrates in plant feedstocks is the polysaccharide fraction, such as cellulose and hemicellulose. Cellulose forms the bulk of cell wall material in higher plants, and, as such, is the most widespread and abundant organic polymer.

Cellulose is an insoluble, linear polymer of at least 3000-β-D (1 → 4) linked glucose residues. The enzymatic hydrolysis of cellulose depends on at least three extracellular enzymes. The first group of cellulases (C_1) may attack the cellulose fibres causing a loss of tensile strength and the production of "reactive cellulose" (hydrocellulose). C_x cellulases perform the subsequent depolymerization to low molecular weight disaccharides (cellobiose) and oligosaccharides. The third group of enzymes known as β-glucosidases, catalyze the hydrolysis of these di- and oligosaccharides to glucose. Subsequent utilization of the glucose is an intracellular event since glucose is small enough to diffuse through the cell wall and semi-permeable membrane which surrounds bacterial cells. There are at least seventy species of bacteria, fungi, actinomycetes and protozoa that have the capacity to split cellulose.

Researchers have found that the reactivity or enzyme degradation of cellulose varies inversely with its crystallinity (Ref. 25). The relative crystallinities of cellulosics as determined by x-ray diffraction (Ref. 26) are as follows:

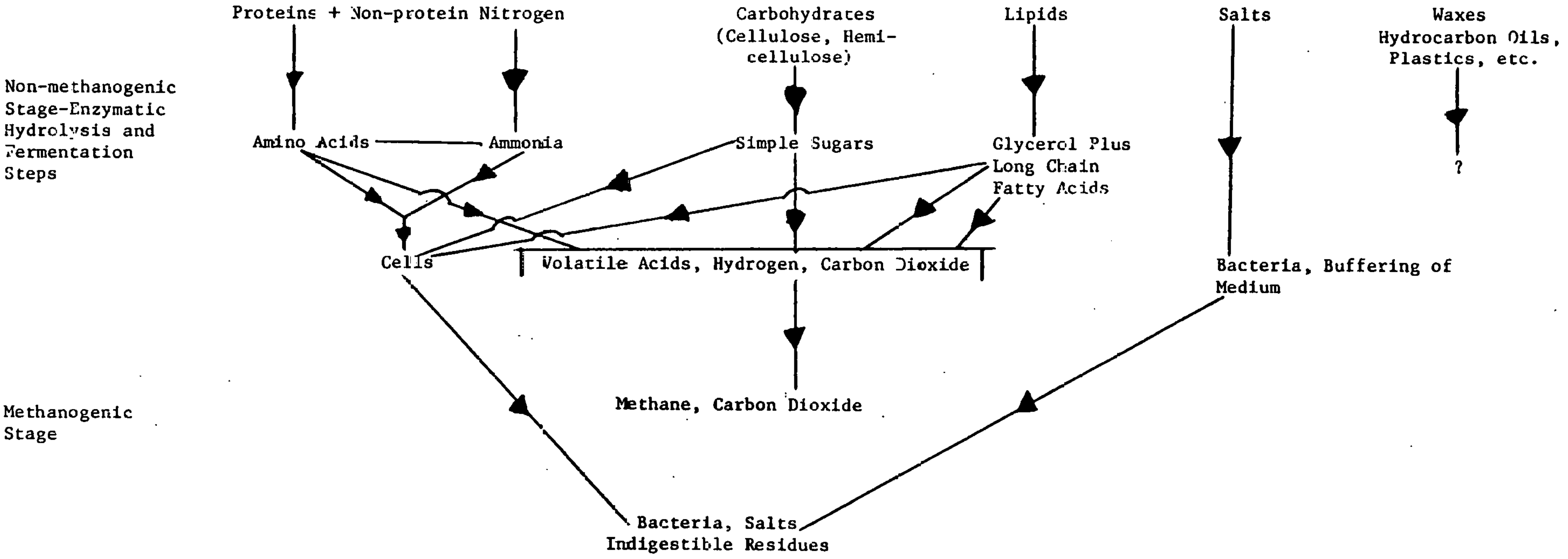


Figure 2.3 Digestion Pathways for the Major Feedstock Components.

Residue	Cellulose	Hemicellulose	Lignin	Lipids	Protein	Ash	C	H	N	O	References
Wheat Straw	50		8.02-18.0	1.25	2.71	4.3-11.0	43.0-53.4	4.2	0.988-4.5	44.0	9, 10, 12, 14, 15, 16
Oat Straw			7.41	2.0	7.74	10.39					12
Barley Straw	52.7	29.2	13.8-15.5			5.5-10.8	43.0	6.0	0.5	45.0	10, 11, 13
Rye Straw	34.0-36.8	27.2	4.7-5.4			2.0					17, 18
Corn Husk	4.28	4.73	0.87	0.12	0.36	0.44					8
Corn Leaf	2.57	2.90	0.60	0.28	0.82	1.60	43.5	6.0	1.5	44.5	8, 10
Corn Stalk	18.54	12.77	5.66	0.92	1.99	2.54					8,10
Corn Cob	7.43	7.94	1.58	0.09	0.60	0.30					8
Total Corn Stover	32.8-40	28.34	8.71-15.1	1.41	3.77	4.3-4.88					8, 9, 11
Soybean Straw	31		17.5-20.1		5.1-6.0						9, 19
Soybean Hulls	45.8-52	17.7	3.2		13.6	5.1					9, 20
Rice Straw	32.1-38.0		3.7-12.5	2.41	4.5-5.1	15.5-19.1	38.5	5.7	0.5	39.8	10, 12, 16, 21, 22, 23, 24
Rice Hulls	42					19.0	35.8	5.4	0.6	39.1	9, 10
Total Cotton Gin Waste						1.3-6.1	47.3	6.0	1.6	39.0	10
Cotton Seed Hulls	60		23.31	1.51	5.53	3.25					9, 12

Table 2.14 Chemical Compoisition of Crop Residues (expressed as a percentage of dry weight).

cotton linters (raw)	72.8
wheat straw	46.6
rice straw	43.3
cottonseed hulls	42.0
oat straw	38.7

Hemicellulose is a collective and somewhat imprecise term for a group of polysaccharide materials having no structural relationship to cellulose but from which they can be separated by alkaline extraction. These materials are a heterogeneous mixture of linear or highly branched polymers which may contain L-arabinose, D-xylose, D-mannose, D-glucose, D-galactose, 4-O-methyl-D-gluconic acid and D-gluconic acid. They are subdivided into that fraction which precipitates on acidification (hemicellulose A or cellulosans) and the supernatant (hemicellulose B or acidic hemicellulose). Hemicellulose A is predominantly composed of β-D (1 $\rightarrow$ 4) linked xylose units - described as xylan , and hemicellulose B is an uronic acid-containing pentose polymer. Plant materials ususally contain hemicellulose: cellulose in the ratio of 0.5:1 or 1:1.

The enzymatic hydrolysis of xylan bears obvious similarities to cellulose breakdown. Xylonases depolymerize xylan to disaccharide (xylobiose) which is subsequently hydrolyzed to its monosaccharide components by xylobiase. A wide variety of microorganisms are involved in the total degradation of hemicelluloses - as would be expected by the large range of substrates.

Next to cellulose and hemicellulose, lignin is the most abundant constituent of organic materials of plant origin. Since lignin is difficult to break down the rates of reaction are retarded with feedstocks high in lignin. Digestibility is increased by separation of the lignin fraction from the cellulose fraction, so that degradation of the latter can occur. Anaerobic bacteria are not known to attack the lignin unless its chemistry is altered.(See Section 3.1.2).

Wood (Ref. 27) reports that cellulose, as it occurs in straw, is not an ideal substrate for digestion in that the less crystalline regions are rich in lignin and hemicellulose and these substances have a pronounced effect on the rate of enzymatic attack on the fiber. Therefore, pretreatment is needed before digestion. The lignin serves to shield or protect the cellulose from bacterial degradation. Hobson _et al_. (Ref. 28) note that in its native form in plant structure, or specialized constituents such as cotton fibers, cellulose is highly polymerized. In addition the fibers may be coated with wax or interlocked with lignin and other polysaccharides, thus shielding the cellulose from bacterial attack.

Prasad _et al_. (Ref. 29) have shown that in the batch digestion of cow dung with vegetable wastes such as sugarcane and groundnut shell, the lignin-cellulose complex is more resilient to decomposition than the ligno-hemicellulose complex: A holocellulose:lignin ratio of 2.87:1 resulted in a 5.72% relative decrease in cellulose but with a holocellulose:lignin ratio of 3.54:1 the relative decrease in cellulose was 9.41%.

In the enzymatic saccharification of cellulosic wastes Mandels _et al_. (Ref. 30) concluded that substrates such as rice hulls, and fibrous cotton were very resistant to saccharification (less than 5% saccharification at 50°C in 48 hours was obtained using the cellulase _Trichoderma viride_) because of low available surface area, high crystallinity and in the case of rice hulls, high lignin content.

Proteins

The protein component of most plant materials is low, usually about 8%. In the digestion process proteins are hydrolyzed by extracellular enzymes. The long chain polymers are broken down into small fragments such as peptides and amino acids by proteases. A pure native protein, when present in a medium as the sole source of carbon and nitrogen, is resistant to attack by even the most proteolytic bacterial species. If, however, a small amount of peptone is added to the medium multiplication of the organisms and degradation of the protein occur. This indicates that an extracellular enzyme is necessary to convert the indiffusible protein into diffusible fractions. In the absence of an available nitrogen and carbon source, the organisms are unable to multiply and elaborate this necessary enzyme. However, peptone can enter the cell and stimulate the organisms to produce the necessary proteolytic enzyme.

Lipids

Lipids in plant material are broken down to glycerol and long chain fatty acids during digestion. Lipids consist of triglycerides (esters of higher fatty acids with glycerol), phospholipids, cholesterol, waxes and fixed oils. The chain lengths of 16-18 carbon atoms are the most common components of fats of animal and vegetable origin these include the saturated acids, palmitic ($C_{15}H_{31}COOH$), stearic ($C_{17}H_{35}COOH$) and the unsaturated oleic acid ($C_{17}H_{33}COOH$). In addition fats and fatty acids of bacterial and fungal origin are not uncommon and include acetic (CH_3COOH), propionic (C_2H_5COOH), butyric (C_3H_7COOH) and a range of branched chain fatty acids (6-methyloctanoic, phthoic). Lipase enzymes are responsible for the conversion of lipids to glycerol and fatty acid. The enzyme is common in plants and also found in aerobic and anaerobic organisms.

Nutrients

Macronutrients including carbon, nitrogen, sulphur and phosphorus are essential to sustain cultures of anaerobic bacteria. Sanders and Bloodgood (Ref. 31) report a minimum C:N ratio of 16:1 necessary for anaerobic digestion. Hill (Ref. 32) found that C:N ratios of between 20-52, 6:1 caused no deleterious effects on the digestion process. Hadjitoti (Ref. 33) has shown that from 2 to 60 mg of nitrogen and from 1 to 10 mg of phosphorous per gm of cellulose are required for decomposition. According to Helmers et al. (Ref. 34), the phosphorus content in bacterial cells is 1.02%, while the nitrogen content is about 8.0% and therefore the phosphorus requirement for bacterial cell synthesis is about one eighth the amount of nitrogen required. The levels of nitrogen and phosphorus required to sustain decomposition vary with the organisms involved but are generally of the same order of magnitude.

Section 3

PRETREATMENT

Fuel gas production from crop residues can be enhanced by use of a pretreatment process to produce water soluble molecular fragments. The cellulosic fraction of the residue is broken down into simple wood sugars. The complex benzene ring structure of the lignaceous fraction of the residue is broken down into low molecular weight aromatic acids and other organic fragments. These reactions can be carried out with a high conversion of total carbon at temperatures of up to 150°C and corresponding pressures near 22 atmospheres. It is anticipated that a staged reactor will be used for this conversion.

The first stage is conversion of both the cellulosic and lignaceous fractions of the residue to simple compounds, largely wood sugars and benzenecarboxylic acids. Anaerobic fermentation, the second stage, is subsequently carried out to produce methane. In the second stage an entire array of the simple molecular organic species is utilized and converted to fuel gas. This bioconversion of pretreated organics takes place at a temperature of up to 65°C and at atmospheric pressure. As with all anaerobic fermentations, approximately 6% by weight of the organic feed, in this case the water soluble aromatic acids and sugars, are utilized by the microorganisms to grow additional cells. This biomass is a potentially valuable by-product as an animal feed.

Following is a technical discussion of the crop residues to fuel gas bioconversion process. First is presented background on the primary stage pretreatment reaction. Then a discussion of the second stage fermentation of pretreatment products to methane is given in Section 3.2.

3.1 Conversion of Crop Residues to Simple Fermentable Compounds by Aqueous Alkali Oxidation

The concept for the first stage reaction is the conversion of both the cellulosic and the complex aromatic structure or lignaceous fractions of crop residues to simple water soluble compounds, readily fermentable to methane. Conversion of residues to simple fermentable compounds by aqueous alkali oxidation is based on experimental work with wood and with coal. For this systems evaluation a discussion of cellulose treatment techniques and methods for treating lignaceous material such as coal are pertinent.

3.1.1 Related Background on the Utilization of the Cellulosic Fraction of Crop Residues

There are many references in the literature relating to experiments on the hydrolysis of cellulose. Many of the early workers carried out experiments on cellulose acid hydrolysis in strong acid and at low temperatures - usually fuming hydrochloric acid or 50% and stronger sulfuric acid and at ambient temperatures or below. In 1945, Jerome F. Saeman of the U.S. Forest Products Laboratory, Madison, Wisconsin carried out a classic investigation on the hydrolysis of cellulose in dilute acid and at high temperature (Ref. 35). This work of Saeman's was a part of the program authorized by the War Production Board to develop a commercially practical method for the conversion of wood to sugar by acid hydrolysis and the subsequent anaerobic fermentation of the sugar to ethyl alcohol. Unfortunately, in this work no study was made of sugar de-composition products, attention being solely confined to the factors affecting the disappearance of the sugar. As a result, no quantitative estimate can be made of the potential conversion to methane of the many soluble fragments formed in these experiments. Later work by Harris (Ref. 36) showed that potentially fermentable organic acids could be created through acid hydrolysis.

Treatment of lignocellulosic materials with alkali, on the other hand, has been found to improve the biological availability of the cellulosic fraction of these materials, increasing both the rate and extent of enzymatic breakdown. This phenomenon has been conclusively demonstrated for a wide variety of lignocellulosic substrates, as measured by such criteria as increased ruminant weight gain on treated material, and by various in vitro measures of digestibility. Table 3.1 summarizes results of some alkaline pretreatment studies, in terms of substrates, treatments employed, and resulting improvements in digestibility. It is clear from Table 3.1 that the increases in digestibility obtained with alkaline pretreatment are substantial for every material tested. It is therefore pertinent to review the mechanism of alkaline pretreatment with reference to the chemical stoichiometry and kinetics of changes occurring in treated substrates.

Resistance to microbial degradation is obviously to the advantage of any plant. All plants have to a greater or lesser degree evolved structurally in ways which confer resistance to attack by microorganisms. The effectiveness of alkaline pretreatment results from its ability to disrupt native plant structure both physically and chemically so that the digestible structural components of the plant, mainly cellulose and lignocellulose, become more accessible to enzymatic breakdown.

Complex chemical and physical changes occur on treatment of wood fibers with alkali. Chemical changes in wood have been studied extensively, particularly by Tarkow and co-workers (Ref. 37). Upon treatment of woods with mild alkali, the first and most rapid reactions occurring are the scission or saponification of acetic acid from the acetyl esters of xylan (polypentose fraction of wood) and the hydrolysis of methoxyl groups as methanol from the methyl esters of xylan and the phenolic moieties of lignins. These phenomena are accomplished by the appearance of free acetate ion and methanol in solution, which can be assayed chemically, providing a convenient means for measuring the extent of reaction. In addition, other ester bonds which crosslink cellulose, hemicellulose and lignin, are hydrolyzed. The scission of the esteric crosslinks has been demonstrated by increased calcium ion exchange ability of the alkaline treated wood (Ref. 38). Macroscopic physical changes

Table 3.1

Effect of Alkaline Pretreatment on Bioconversion of Various Substrates

Reference	Substrate	Criterion of Bioconversion	Treatment Employed	Bioconversion Without Treatment	Bioconversion With Treatment
Bellamy (41)	Feedlot waste fiber from manure	Growth of single cell protein on fiber; reductions of cellulose by organisms	0.05M (0.2%) NaOH 4 hrs and 20 hrs at 23°C	15-20% (cellulose utilized)	74-81% (cellulose utilized)
Moore et al (41a)	Aspen pulp	Solids reduction in the presence of cellulose enzymes	1% NaOH 1 hr 30°C	10%	50%
Ghose et al (41b)	Jute fibers	Solids reduction in presence of Rumenococcus culture	1% NaOH 1 hr 100 °C	~5%	80%
Dunlap (41c)	15 different lignocellulosic substrates	Reduction in cellulose by rumen organisms	10% NaOH 1 hr 30°C	Average 85% increase in digestibility for 15 substrates	
Wilson and Pigden (42)	Wheat straw	Solids reduction by rumen fluid	5 grams NaOH / 100 grams straw 2-3 weeks ~20°C	33%	63%
Wilson and Pigden (42)	Wheat straw	Solids reduction by rumen fluid	7 gms NaOH / 100 gms straw 2-3 weeks ~20°C	33%	80%
Wilson and Pigden (42)	Poplar wood	Solids reduction by rumen fluid	3 grams NaOH / 100 grams wood 2-3 weeks ~20°C	5%	20%
Wilson and Pigden (42)	Poplar wood	Solids reduction by rumen fluid	7 grams NaOH / 100 grams wood 2-3 weeks ~20°C	5%	50%
Stranks (41d)	Wheat straw	Gas evolution during digestion by rumen fluid	5% NaOH 18 hours 20°C	60% increase in rate of gas evolution with treatment	

which occur in the wood have been extensively documented (Refs. 37,39). It is sufficient to state that the over-all effect of treatment is to cause a "breaking up" of the wood fiber structure allowing greater access by enzymes and greater digestibility. Evidence for increased accessibility to high molecular weight materials is given by Feist, et al. (Ref. 40) who showed increasing permeability of wood to a series of well-characterized polyethylene glycols of increasing molecular weight.

It is pertinent to note that when the above-mentioned changes reach completion, digestion appears to reach a ceiling and cannot be increased. For example, Bellamy (Ref. 41) found no increase in digestibility when the time of pretreatment of feedlot waste fiber with 0.2% NaOH was increased from 4 hours to 20 hours, although NaOH was present in excess. Wilson and Pigden (Ref. 42) found no increase in digestibility for either wheat straw or poplar wood when the concentration of NaOH was increased above 7 grams per 100 grams of material, although digestibility increases were linear with alkali addition below this level. The digestion ceiling obtained for cellulose with alkaline treatment is generally 70-90%, although solids reductions are of course lower depending on the lignin content of the material. When treatments are more severe, significant destruction of the hemicellulose fraction of wood occurs, as has been amply demonstrated in paper pulp manufacture (Ref. 43). This may also be accompanied by formation of toxic byproducts (Ref. 44). Hence, it appears that a fairly mild degree of alkaline pretreatment is effective, and that over-treatment may be either of no benefit or harmful.

Although the physiochemical changes in plants other than wood have not been investigated thoroughly, it is probable that the mechanism is similar, namely an opening up of structure and increased accessibility to enzymatic attack. The increases in digestibility for alkaline treated wheat straw, jute, and bagasse seem strong evidence for this.

The stoichiometry and kinetics of alkaline pretreatment in combination with the resulting increases in digestibility determine the economics. The total alkali requirement is largely dictated by the number of free carboxyl groups created when the required saponification reactions go to completion. Tarkow and Feist (Ref.37) have shown for treated sugar maple that the alkali required to neutralize the carboxyl groups freed on the xylan chains amounts to 23 meq/100 grams, and that required to neutralize the acetate is about 110 meq/100 grams, for a total of 133 meq/100 grams of wood. Hence the amount of NaOH (equivalent weight = 40) or of $Ca(OH)_2$ (equivalent weight = 37) to carry out complete saponification and attain maximum digestibility of maple wood would be about 5% of the wood weight. The data of Wilson and Pigden (Ref.42) indicate that 7% NaOH based on the weight of wheat straw or poplar wood gave maximum digestibility.

The kinetics of saponification appear to be quite rapid. Tarkow and Feist (Ref.37) show that saponification of maple wood was essentially complete at the end of 3 hours in the presence of 0.5% NaOH. Saponification time varied inversely with base concentration, indicating a first order reaction with respect to hydroxyl ion. Similarly, the data of Bellamy indicated that maximal digestibility of feedlot waste fiber was attained in the presence of 0.2% NaOH at the end of 4 hours. On the basis of these limited kinetic data, it appears that required saponification reactions could be completed in less than 1 day at 37 - 40°C in the presence of a sufficient quantity of a sparingly soluble alkali such as slaked lime (solubility ≈ 0.1%).

3.1.2 Related Background for Aqueous Alkaline Oxidation of Lignin in Crop Residues

There is a long background of scientific experimental work on the aqueous alkaline oxidation of the type of lignin material found in crop residues in order to produce simple water soluble organic compounds. Much of the experimental work on the aqueous oxidication of coal is directly related to the lignaceous fraction of crop residue pretreatment process; for this reason this work is reviewed. The work may be divided into several historic areas which lend to the technical discussion. Early work was carried out from the time of the

First World War, in Germany, largely, as well as in the United States, and up to the time of the Second World War. This is well documented and reviewed by H.C. Howard (Ref. 45). Additional experiments on alkali oxidation of lignaceous materials such as coal were continued after the war and into the 1950's by the Coal Research Laboratory of Carnegie Institute of Technology, where most American work in this area has been conducted. Also, Dow Chemical Company had a pilot plant for production of chemicals from coal. This American work did not continue, apparently due to the overwhelming growth of the petrochemical business after the war and the impact of this growth on the potential for coal chemicals. However, during the 1960's some interest in Japan in the potential for chemicals from coal resulted in initiation of an experimental program in aqueous alkaline oxidation of coal. At the same time, and continuing through today with very intensive interest, there has been Russian work in this area.

3.1.2.1 Early Experimental Work

The most significant results obtained in studying the breakdown of lignaceous material such as coal by oxidation reactions have been those obtained in experiments with alkaline media. It has been shown that over 80% of typical lower rank coals can be recovered in the form of water-soluble compounds. Experiments on lower rank coals such as lignite are of special interest in evaluating the potential for application of such processing techniques on the lignaceous fraction of crop residues. Work in this area was first carried out by Fisher, et al. (Refs. 46,47, 48). To a large extent this early work was done to establish the presence of aromatic structures in bituminous coal. Substantial amounts of benzenecarboxylic acid were obtained when coal was reacted with 2.5 N Na_2CO_3 @ 200°C followed by a 400°C "pressure/heating treatment." The amount of aromatic acids increased substantially with this treatment, as would be expected. Of special interest in the earlier work in this area is that oxalic acid and acetic acid were also identified in meaningful quantities (Ref. 49), along with the benzenecarboxylic acids, indicating that the aromatic acids separated from the coal structure were also subsequently cleaved in the reaction. This suggests the possibility of a continuous plug flow reactor or of a staged reactor with programmed temperatures and pressures throughout the length in order to optimize the conversion.

Smith, et al.(Ref. 50) carried out the detailed analysis of the alkaline hydrolysis of a Pittsburgh bituminous coal. Several other types of coal and carbonaceous materials were also evaluated, ranging from an Illinois bituminous coal to anthracite and also graphite. It was found that with the lower rank coals a significant fraction of the carbon was recovered as simple organic acids. From the materials of rank higher than a low temperature coke, however, decreasing recoveries of organic acids were obtained. The organic acids obtained, at temperatures of 200 to 250°C, were oxalic, trimellitic, pyromellitic, prehnitic, and terephthalic acids.

Overall, this earlier work clearly demonstrated the feasibility of obtaining low molecular weight organic aromatic acids from coal by aqueous alkaline oxidation. The work especially points to utilization of lower rank coals such as lignite. Further projection of this work indicates that the lignaceous fraction of crop residues would be a highly suitable feedstock for such a processing technique if the subsequent bioconversion resulted in a significantly higher fuel gas yield to offset higher capital and operating costs.

3.1.2.2 Post Second World War American Work

In a 1951 publication (Ref. 51) from the Coal Research Laboratory of Carnegie Istitute of Technology alkali treatment of bituminous coal was described. A 12% by weight suspension of 100 mesh coal in a 36% sodium hydroxide solution was treated with oxygen at a pressure of 60 atmospheres at 270°C for up to 3 hours. The yield of mixed organic acids recovered was approximately 60% by weight of the bituminous coal charged. These acids ranged in molecular size from the simple aliphatic acids, acetic and oxalic, through the benzene-carboxylic series to water-soluble polycarboxylic aromatic acids of size larger than the benzene ring. Dark-colored alkali-soluble, acid-precipitable "humic acids" (Ref. 51) of undetermined structure were also recovered.

Franke, et al.(Ref. 52) reported on extensive continuation of the above work (Ref.53). This work included small pilot plant (150 lb batches of coal) experiments. Also, the preliminary design of a plant for producing "coal acids" from 30 x 10^6 pounds/year of coal was discussed. It is of interest to note that reaction conditions for these larger scale aqueous alkaline oxidation experiments were "standard" at 270°C and 60 atmospheres. A bituminous coal was used. As with the earlier work (Ref.51) oxalic acid and acetic acid were formed, as well as benzenecarboxylic acids. Approximately one-third of the recovered products were identified as certain benzenecarboxylic acids. For chemical production these pure compounds need to be separated; however, for anaerobic fermentation to methane essentially all simple organic molecular fragments from the reaction will be readily utilized.

Dow Chemical Company (Ref. 54) carried out experiments following very closely the work of Howard's group. Overall the goal was to produce organic acids from coal. Utilization of alkali from Dow's chlorine production facilities was another incentive for carrying out these experiments. The major component from the coal oxidation was a light-yellow colored water-soluble mixture of aromatic acids. The average molecular weight of these "coal acids" was 270. While separation of these acids into individual components was found to be difficult, no separation is required for fermentation.

In a subsequent paper (Ref. 55) by the group led by H.C. Howard the first interest and experiments on a subbituminous coal were reported. Specifically, the reaction with aqueous alkali on a Wyoming subbituminous coal was studied in a batch reactor over a temperature range of 200-425°C at alkali (NaOH) concentrations from 1 normal to 66% by weight and in an inert atmosphere. By some rather preliminary experiments, the conditions selected as "optimum" for degradation of the Wyoming subbituminous coal were 250°C, 5N NaOH, and a 24 hour reaction time. It should be noted that the conditions described may be not optimum. Further, breakdown of the lignaceous fraction of crop residues to many fragments of moderate molecular weight for anaerobic digestion may require conditions other than presently documented for coals.

A theoretical result from these experiments which may have practical merit for crop residues is that the enrichment in oxygen and hydrogen of the products from the coal took place by reason of the reaction of the coal with the water. That is, based on the yields and compositions of the products formed, it was found that excess oxygen and hydrogen were in the ratio of approximately 8:1. Had the reaction yielded oxygen to hydrogen in the ratio of 16:1, then the hydroxyl groups present in the alkali might have contributed to the conversion. It is concluded that the reaction is catalyzed by the alkali and that the alkali does not contribute quantitatively in the reaction.

3.1.2.3 Recent Japanese and Russian Experimental Programs

In the early 1960's, a number of papers (Refs. 56,57,58,59) were published by Yashia Kamiya on the aqueous alkali oxidation of Shikamachi, a Japanese bituminous coal. The purpose of this series of experiments was to obtain optimum yields of benzenecarboxylic acids. For an oxygen-enhanced oxidation at 250°C in aqueous sodium carbonate the following products were obtained (Ref. 57).

Products	% of Coal Carbon
Aromatic Acids	37.2
Oxalic Acid	4.0
Water-Insoluble Acids	5.1
Carbon Dioxide	49.8
Residue	1.2
	97.3

The aromatic acids formed were later (Ref. 58) separated - about 45% of the aromatic acids were benzenecarboxylic acids or about 26% of the original bituminous coal reacted.

Later Kamiya (Ref. 59) carried out the partial decarboxylation of the aromatic polycarboxylic acids as a means of complete recovery and separation of potentially valuable components from the coal oxidation products. Subsequently, experiments were carried out (Ref. 56) to specifically form benzenecarboxylic acids from aromatic compounds by further oxidation in alkaline media.

It is pertinent to consider the application of these experiments to crop residues for the continuous production of soluble organic compounds suitable for bioconversion to fuel gas. A plug flow reactor or a series of staged reactors may be considered in which the residue fragments initially broken down may be bioconverted to fuel gas. It is anticipated that wood sugars will be the initial breakdown products from the cellulose in the residue. Subsequent reactors, each at increasingly more severe conditions, may result in continuous breakdown of the more complex lignaceous structure of the residue. Overall then, rather than a spectrum of products from carbon dioxide, to wood sugars, to heavy polyaromatic acids, as with a batch reactor, it may be anticipated that the proper engineering design will result in a less broad spectrum of products yielding larger amounts of wood sugars and the low molecular weight benzenecarboxylic acids and minimal amounts of higher molecular weight aromatic acids.

It has been seen in the above review that the American work on aqueous alkali oxidation of coal, directly related to the lignin in crop residues, has been carried out largely under the direction of H.C. Howard in Pittsburgh. However, perhaps the most intensive work in this area has been carried out only recently by the Russians. A search in <u>Chemical Abstracts</u> from 1962 thru 1973 revealed thirty-five Russian publications. T.A. Kukharenko is the leading author among these many publications. Overall, the following progress is evident: a) lower rank coals including lignite have been studied under aqueous alkaline oxidation conditions, b) reaction conditions are being carefully defined with the goal of optimizing production of benzenecarboxylic acids, c) reactor design concepts are being evaluated - a two stage plug flow reactor is of current interest to the Russian workers.

In a recent article, Kukharenko (Ref. 60) reports that nearly complete (74 to 100%) conversion of coal into a soluble form has been obtained. From 40% to 78% of the products are carboxylic acids. It is interesting that up to 30% of this product acid mixture is oxalic acid. The two-stage process, using either NaOH or K_2CO_3, is conducted at up to a temperature of 270°C. Unfortunately, no reaction kinetics are presented on which to base reactor design and scale-up. There appears to be a very strong continuing interest in Russia in the production and recovery of aromatic acids from lower rank coal.

In addition to oxidative reactions with coal, several studies have been made of lignin decomposition with gaseous oxygen under alkaline conditions (Refs. 61, 62). The yields after the alkaline-oxidative reaction indicate the formation of acidic materials. Grangaard at Kimberly-Clark Corp., Neenah, Wisconsin (Refs. 63,64) reports that various types of lignin can be almost completely degraded by oxygen in an alkaline solution to yield reaction products that contain 80% acetic, formic, and oxalic acids, readily digestible by anaerobic microorganisms.

3.2 Methanogenic Fermentation of Water Soluble Organic Compounds from Pretreatment

As described above, the first stage of this process is to convert crop residues into simple water soluble benzenecarboxylic acids and wood sugars by an aqueous alkali oxidation process. The second stage in the overall residues to fuel gas conversion is the anaerobic fermentation of these benzenecarboxylic acids and wood sugars to methane and carbon dioxide. The anaerobic conversion of sugars to methane has been carried out using C-14 labeled tracers at both mesophilic and thermophilic conditions (Ref. 65). Further details of wood sugar bioconversion are given in the textbooks (Refs. 66,67). More discussion, however, is required with respect to anaerobic conversion of possible aromatic compounds obtained from pretreatment of the lignaceous fraction of crop residues.

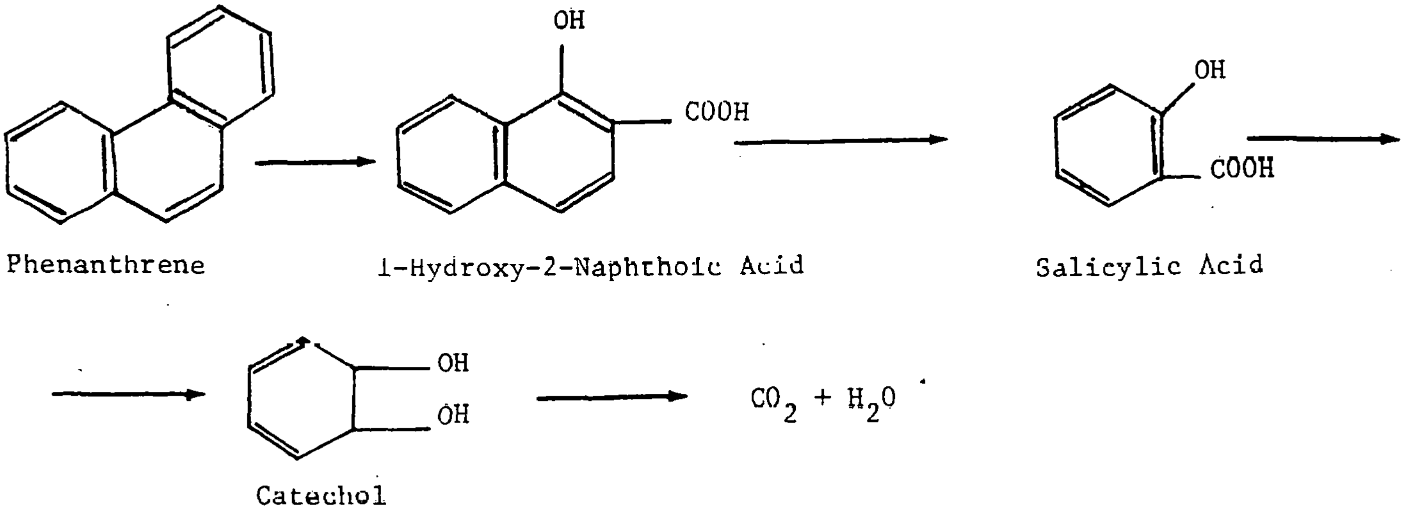
3.2.1 Anaerobic Conversion of Aromatic Compounds

Clark and Fina (Ref. 68) carried out experiments to demonstrate that benzenecarboxylic acid could be anaerobically fermented. Using sewage sludge digester effluent as the methane producing microbial culture, yields of product gases as high as 90% of the theoretical yield were obtained. Benzoic acid was the only fermentable carbon source supplied to the fermenter flasks. It was also demonstrated during these experiments that as long as this aromatic acid was added, the culture would yield methane and carbon dioxide. It was found that varying amounts of gas could be obtained by increasing or decreasing the concentration of the benzoic acid feed. In a fermenter converting daily 80 - 90% of the substrate fed every 24 hours, withholding feed led to a rapid depletion of the substrate in the fermenter and a corresponding cessation of gas production. It was further found that if more benzoic acid was then added that the gas evolution started again almost immediately. The product gases from this anaerobic fermentation of benzoic acid were analyzed to be 42.5% CO_2/57.5% CH_4 and 46.9% CO_2/53.1% CH_4 (the data reported from the two fermenters tested). Clearly, the rapid conversion of simple aromatic acids at high yields was established.

Earlier Tarvin and Buswell (Ref. 69) reported the complete bioconversion to methane and carbon dioxide of benzoic, phenylacetic, hydrocinnamic, and cinnamic acids. Here too, the culture of microorganisms was obtained from a sewage sludge anaerobic digester. Bioconversion of benzenecarboxylic acid was to 54.5% CH_4/45.5% CO_2 for the two experiments reported. The percentages of CH_4/CO_2 in the gas mixture produced in the anaerobic fermentation of phenylacetic, hydrocinnamic, and cinnamic acids were 58/42, 60.5/39.5, and 58/42 respectively

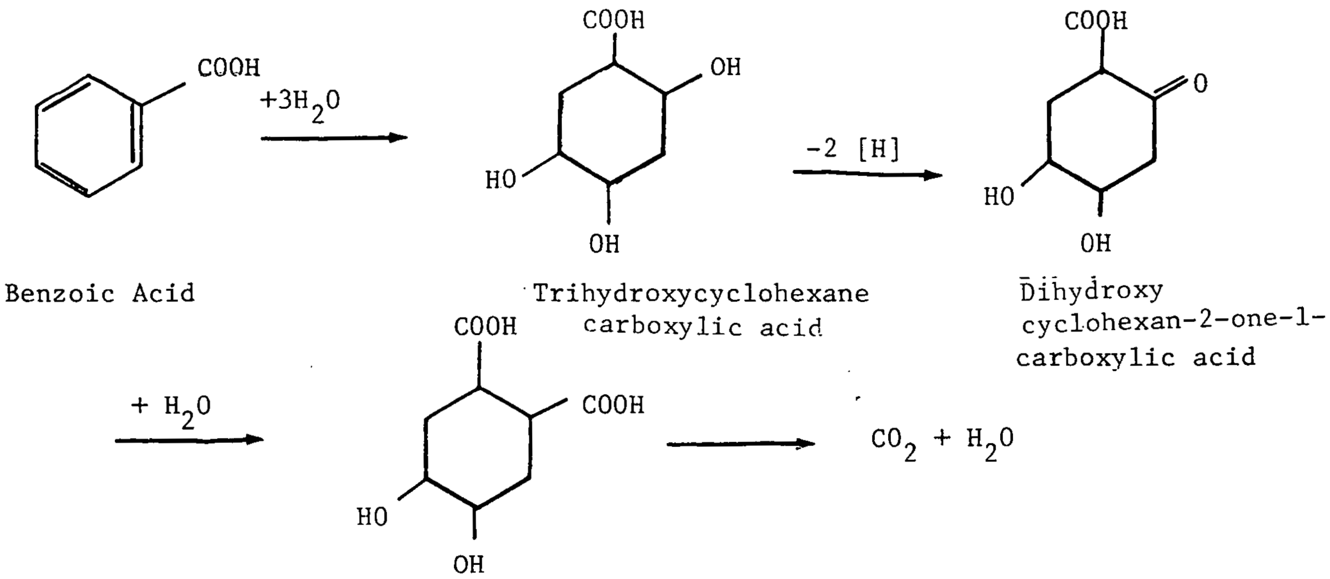
The above cited production of methane and carbon dioxide from benzoic acid by anaerobic fermentation was the first reported in the literature. Except for this early work of Tarvin and Buswell and later confirmation by Clark and Fina (Ref. 68), it had been considered by all other investigators that the aromatic ring could not be cleaved and then fermented unless oxygen was present. Fina and Fiskin (Ref.70) later carried out detailed radioactive tracer experiments showing explicity that benzoic acid was converted to methane and carbon dioxide in a fixed ratio with a conversion efficiency of greater than 95%. Further, on a theoretical basis, they postulated that the anaerobic bioconversion proceeded by a different metabolic pathway than when done aerobically.

With respect to possible metabolic pathways of aromatic compounds, the historic study on the anaerobic conversion of phenanthrene by Rogoff and Wender (Ref. 71) is pertinent. Experiments were conducted with pure cultures of bacteria obtained through a soil enrichment technique and capable of utilizing phenanthrene as a sole carbon source. The following possible pathway was presented (from Ref. 71):



Evans (Ref. 72) has also presented possible pathways for the oxidative bioconversion of aromatic compounds. Evans points out that the distinctive biochemical step is ring cleavage, although he postulates that enzymes first convert the aromatic substrates into an ortho or para dihydroxyphenol derivative prior to cleavage of the ring to aliphatic acids.

While it is clear that the pathway for the anaerobic breakdown of the aromatic ring is different and quite distinct from the aerobic pathway the foregoing postulates are helpful. Indeed, Taylor et al.(Ref. 73) isolated a bacteria that utilized a range of aromatic compounds either aerobically or anaerobically. This facultative anaerobic microorganism converted p-hydroxybenzoate within approximately 18 hours. The pathway for the fermentation of benzoic acid was given as (Ref. 73):



dihydroxy pimelic acid
(positions of hydroxyl groups arbitrarily assigned)

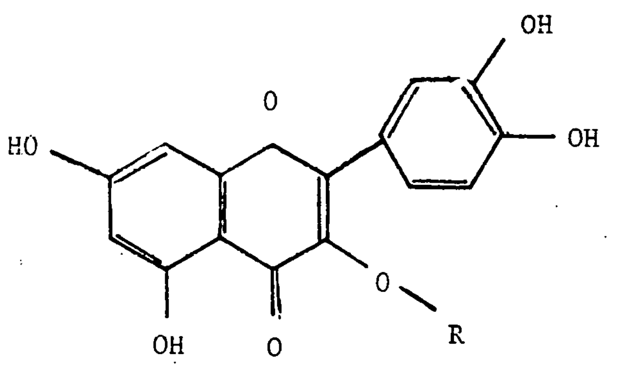
It was only in 1969 that Nottingham and Hungate (Ref. 74) established clearly that molecular oxygen was not necessary for biological cleavage of the benzene ring. In their experiments benzoic acid was converted to methane and carbon dioxide under stringently anaerobic conditions. Specifically, methane was found to constitute 59, 52, 59, and 58% of the product gas in the experiments presented. This is in reasonably good agreement with the 62.5% theoretical yield of methane if benzoic acid is converted to methane and carbon dioxide without the participation of other substrates. The overall stoichiometry of the reaction is:

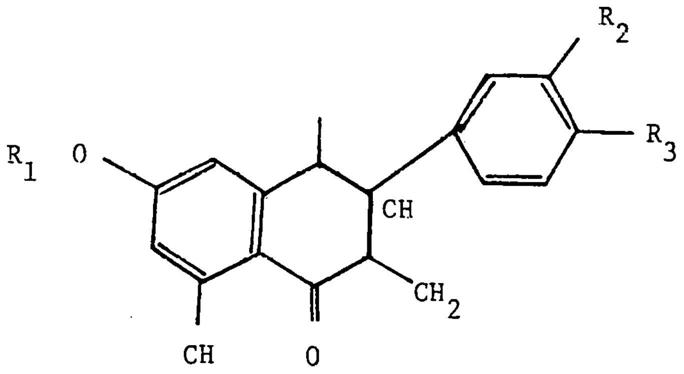
$$4\ C_6H_6CO_2\ \text{(Benzoic acid)} + 18\ H_2O \rightarrow 15\ CH_4 + 13\ CO_2$$

Some of the most recent work on anaerobic fermentation of aromatic compounds appears to be that done under the direction of McCarty at Stanford University (Ref. 75). Here the objective is heat treatment of municiple refuse for increasing anaerobic biodegradability. Alkali treatment at up to 250°C has been found to be most effective in increasing bioconversion to methane. As a part of these studies, selected aromatic compounds expected to be formed from the treatment of lignin, were evaluated. Specifically, benzoic acid, p-hydroxybenzoic acid, protocatechuic acid, and vanillin were found to be readily converted to methane. These promising results give encouragement that lignocellulosic fractions of wood-like materials such as crop residues may be fermented to methane following suitable alkaline treatment.

3.2.2 Supporting Studies on Ring Cleavage

It is important to point out studies on the anaerobic fermentation of rather complex plant formed aromatic compounds, such as bioflavonoids. In 1969, Cheng, Jones, Simpson and Bryant (Ref. 76) presented experimental results on the first recorded demonstration of the degradation of the heterocyclic ring structure of rutin and other bioflavonoids in pure cultures of anaerobic bacteria. The complex structure on some bioflavonoids is given below (Ref. 76):



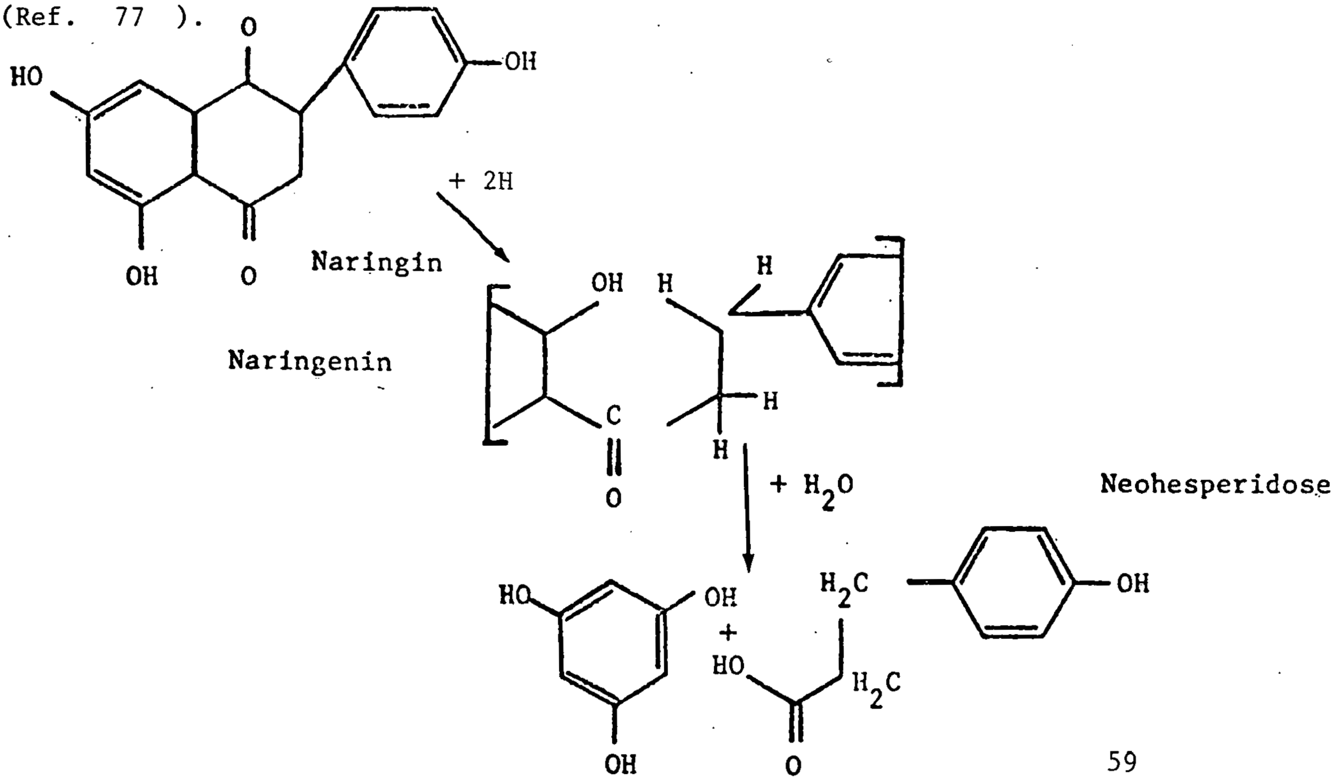


Quercetin R=H
Quercitrin R= Rhamnose
Rutin R= Rutinose

Naringin R_1 = Rhamnoglucose
R_2 = -H
R_3 = -OH
Hesperidin R_1 = Rutinose
R_2 = -OH
R_3 = $-OCH_3$

Structure of Some Bioflavonoids

This work showed that microorganisms (isolated from bovine rumen) are capable of rapid anaerobic degradation of the heterocyclic flavonoid glycosides rutin, quercitrin, naringin, and hesperidin. Several strains of rumen bacteria which actively hydrolyzed the glycosidic bond of rutin also degraded the aglycone. In more recent experiments the products produced by the anaerobic degradation of naringin were identified. Specifically, the postulated pathway for the anerobic degradation of naringin is given by (Ref. 77).



Further anaerobic fermentation to methane and carbon dioxide occurs following this breakdown of the more complex structures.

Supporting studies on the anaerobic fermentation of other complex ring compounds are of value. For example, Evans, et al.(Ref. 78) carried out experiments to determine the bacterial metabolism of 2,4-dichlorophenoxyacetic acid, one of the most widely used of the hormone herbicides. Postulated pathways showing the cleavage of the benzene ring were presented. In a similar manner the biosynthesis and degradation of catechol in plants has been reviewed (Ref. 79). Willetts and Cain (Ref.80) presented results on the microbial metabolism of several alkylbenzene sulphonates, the major components of commercially marketed detergents. While an oxidative conversion, this work further supports other studies that microbial cleavage of an array of aromatic compounds is feasible.

It is of value to note the anaerobic conversion to methane of those organic acids such as acetic acid that may be formed when the benzene ring is cleaved in the first stage alkali oxidation step. While aromatic acids will be present in the product stream from the first stage of the process, there will also be produced substantial amounts of low molecular weight acids. McCarty and Vath (Ref. 81) carried out experiments using both acetic acid and butyric acid as the sole organic substrate to anaerobic fermenters, along with sewage sludge digester effluent as nutrient. They found that maximum rates of acetic acid and butyric acid utilization were 21.9 and 13.3 gm/liter/day, repsectively. Moreover, over 99% of the acetic acid (the only total conversion reported) was converted to methane and carbon dioxide. These above rates of fuel gas production for a water soluble organic acid are almost ten times greater than the maximum rates obtained for complex industrial and municipal wastes. Close control and maintaining optimum environmental conditions for growth of the microorganisms was cited as the basis for these high conversion rates of acetic and butyric acids. These workers (Ref.81) further state that there appears to be no practical limit to the possible rate of volatile acid fermentation to methane when proper environmental conditions are present.

3.3 Temperature Pretreatment

By subjecting organic materials to excessively high or low temperatures, chemical bonds are broken down to yield a product which is more easily susceptible to hydrolytic activity during anaerobic digestion. Methods used for temperature pretreatment include boiling, steaming and freezing. Many industrial wastes have already been thermally treated during normal processing (Refs. 82, 83) and require no further heat treatment. However, in those organic materials which have not been subjected to temperature changes a reduction in both strength and degree of polymerization is possible. Heat treatment has also been applied by steaming lignocellulosic residues including straw (Refs. 84-90) and wood (Refs. 91 - 94). Muller found that steam pretreated hardwoods are more easily digested by ruminates than treated softwoods (Ref. 95). Bender and co-workers (Refs. 93,94) have demonstrated that aspen chips steamed for 2 hours at 100-115 psi are readily accepted by sheep at up to 60% of the total ration.

Work on aqueous oxidation of lignocellulosic material without using alkali has been conducted for many years by Brink and co-workers (Refs. 96,97). Overall, the air oxidation of particulate wood in aqueous slurries from 160-220°C and pressures from 15.3-34.0 atm in staged reactors results in acid product (pH = 2). A portion of this product is then recycled to promote hydrolysis in the first stage using fresh wood chips. Under a conceptually similar research program using air oxidation without alkali, McGinnis and others (Refs. 98,99,100) have investigated the "programmed pyrolysis," i.e., staged reaction, of pine bark, but at somewhat more severe conditions (200-600°C) than Brink. It would appear that the reaction products from cooking the wood chips and bark, like crop residues, would be well suited for anaerobic fermentation to a fuel gas. These results may well point to processing technology for crop residues not requiring the added cost of chemicals.

3.4 Size Reduction of Crop Residues

Although crop residues often have already undergone some size reduction during harvesting operations, further reduction is advantageous to increase degradation rates. Investigation of the effects of the physical modification of cellulosic materials on their digestibility by ruminant - inhibiting microorganisms have indicated that either fine grinding or ball milling is the most effective treatment to date for increasing digestibility of wood and other cellulosic material (Ref. 101). Ball milling not only results in a reduction in particle size but also a reduction in crystallinity, a reduction in mean degree of polymerization, and a marked increase in the fraction of material that is water soluble. The increase in size reduction increases the available surface of both amorphous and crystalline cellulose, thus increasing accessibility to treatment by large enzyme molecules (Refs. 102-108). Data reported by Mandels et al. (Ref. 109) on the digestibility of milled cellulose in relation to time milled indicate that a linear relationship exists between increase in digestibility and increase in milling time. Millett et al. (Ref. 110) notes, however, that the degree of effectiveness of ball milling varies considerably with different materials.

Nelson et al. (Ref. 111) have studied the effect of size reduction pretreatment of crop residue on fuel gas production by anaerobic fermentation. Corn stover was chopped using a silage shredder to 3 mesh and ground to a 200 mesh flour with a rod mill. Wheat straw was chopped and ground with a hammer mill to 3 and 16 mesh. Partially digested sewage sludge was added to each size reduced crop residues to provide the additional nitrogen required for digestion and as inoculum of anaerobic microorganisms. Each residue was tested at fermentation temperatures of 28° to 30°C (mesophilic) and 50° to 55°C (thermophilic). The ground corn stover produced 48% more fuel gas at mesophilic conditions and only 15% more than chopped stover at thermophilic temperature. Size reduction of wheat straw for enhanced fuel production was less significant; ground straw yielded an 11% increase at mesophilic temperature and no increase at thermophilic temperature.

In contrast, Pfeffer (Ref. 112) has found no increase in bioconversion efficiency of corn stover milled to 28 mesh. Mechanical size reduction can significantly increase capital and operating costs of a pretreatment process. It is necessary to investigate further the effect of substrate size reduction on fuel gas production in order to evaluate cost effective options.

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Section 4
ANAEROBIC DIGESTION

Traditionally , anaerobic digestion has been used as a treatment process for industrial and municipal wastes. Fundamental knowledge of the process has grown out of the waste treatment industry. Advancement in anaerobic digestion technology, combined with increased energy costs, has led to an adaptation of the concept for the conversion of biomass to methane as the primary product.

An extensive discussion of anaerobic digestion concepts was presented by Ashare and Wilson (Ref. 113). The choice of process to be utilized with a crop residue is dependent on composition of that residue as well as the scale of the process. In this section, technical descriptions are presented for continuous plug flow and CSTR concepts and for a batch design. In Section 6, the base-line digestion processes used for small farm, cooperative, and utility/industrial sizes are discussed. Variations from these base line designs are discussed in Section 7, in which a sensitivity analysis is presented.

4.1 Continuous Digestion Process

Continuous digestion can be carried out in either a plug flow or continuous stirred tank reactor (CSTR). The major difference between these is that for the plug flow system each particle has the same residence time in the reactor, whereas, for the CSTR there is a broad distribution of residence times. Experience with continuous anaerobic digestion systems has been primarily with the CSTR, and large CSTR digesters are in operation, e.g., sewage treatment digesters. The plug flow concept is still in development. Jewell *et al.* (Ref. 114) are investigating the plug flow anaerobic digestion of dairy cow manure.

Applications of these concepts to digestion of crop residues on a large scale is rare. Pfeffer and Quindry (Ref. 112) have investigated digestion of corn stover in 200 gal. stirred tank reactors, and have noted difficulty in handling high solids content feed. Jewell et al. (Ref. 114) have observed on a pilot plant scale that plug flow digestion of manure with wheat straw resulted in operating problems due to straw flotation. It is apparent that more larger scale development work is necessary, to determine both optimum digestion conditions and material handling properties.

4.1.1 Kinetics of Continuous Digestion

If it is assumed that the digestion process follows first order kinetics, a description of either plug flow or CSTR is obtained utilizing chemical reaction engineering theory (Ref. 115). For first order kinetics

$$\frac{dC_B}{dt} = -kC_B \qquad (4.1)$$

where C_B is the concentration of biodegradable volatile solids, k is the first order reaction rate constant, and t is time. A material balance can be performed around the reactor,

material out = material in - material reacted

which gives, for the CSTR

$$C_{Be} = C_{Bo}/(1 + k\tau) \qquad (4.2)$$

and for the plug flow system

$$C_{Be} = C_{Bo} \exp(-k\tau) \qquad (4.3)$$

where C_{Bo} is the inlet concentration, C_{Be} is the exit concentration, and τ is the hydraulic retention time (defined by reactor volume ÷ inlet volumetric flow rate). A comparison of Eq. (4.2) and (4.3) indicates that for the same retention time, the plug flow system will result in a greater substrate utilization, i.e. a lower exit concentration.

The gas production is given by

$$G_{CSTR} = A\ (C_{Bo} - C_{Be}\ )$$

$$= AC_{Bo}\ k\tau/(1-k\tau) \qquad (4.4)$$

and

$$G_{PLUG} = AC_{Bo}[\ 1-\exp\ (-k\tau)] \qquad (4.5)$$

where A is the volume of gas produced per mass converted.

The rate of gas production is found from the derivatives of Eqs. 4.4 and 4.5 (with respect to τ),

$$\dot{G}_{CSTR} = AC_{Bo}k/(1-k\tau) \qquad (4.6)$$

$$\dot{G}_{PLUG} = AC_{Bo}k\ \exp\ (-k\tau) \qquad (4.7)$$

where $\dot{G}$ is the volume of gas produced per reactor volume per day (VVD).

Experimental data are used to determine C_{Bo} and k in order to use the above relationships for system design. The value of C_{Bo} can be obtained from digestion results by extrapolation to infinite retention time. The reaction rate constant k can be determined by fitting digestion data to Eq. 4.4 or 4.6 and using a least squares regression analysis. Descriptions of these techniques are presented by Ashare et al. (Ref. 116) and Pfeffer and Quindry (Ref. 112).

Ashare <u>et al.</u> (Ref. 116) have shown that an Arrhenius type relationship exists for k,

$$k = k_o \exp(-E_a/RT) \qquad (4.8)$$

where $k_o = 5.9 \times 10^9$ days $^{-1}$ and the activation energy, E_a, is approximately 15 kcal/mole. (R is the gas constant and T is the absolute temperature). This result is an average for many different sources of biomass. For a specific biomass and digestion conditions it is possible that the rate constant will deviate from that predicted by Eq. 4.8. For example, for a temperature of 59°C, Eq. 4.8 gives k = 0.61 days^{-1}, whereas Pfeffer and Quindry (Ref. 112) obtained a value of 0.25 day^{-1} for digestion of corn stover at 59°C. This difference is significant and leads to the conclusion that experimental results should be utilized rather than a generalized relationship such as Eq. 4.8.

4.2 Batch Digestion Process

The use of low capital cost "hole in the ground" batch digestion systems have been proposed for use with crop residues. This approach is similar to disposal of municipal solid refuse, which has traditionally been accomplished in sanitary landfills. Recently, interest in this process has extended to the production of methane from biomass with a high solids content, such as food processing wastes and agricultural residues.

The first formalized description of the sanitary landfill method of disposal was in the form of an ASCE Committee report published in 1959. The operational procedures drawn up in the report are summarized in the ASCE definition of a sanitary landfill, which is: "Sanitary landfilling is a method of disposing refuse on land without creating nuisances or hazards to public health or safety, by utilizing the principles of engineering to confine the refuse to the smallest practical volume, and to cover it with a layer of earth at the conclusion of each day's operation or at much more frequent intervals than may be necessary." (Ref. 117). The guidelines were geared toward aesthetics and did not take into consideration the possibility of pollution of the surrounding atmosphere and groundwater.

Anaerobic conditions usually exist in all but the top 10 feet of a landfill, resulting in the production of gases and leachates. Lack of control of these contaminants has resulted in fires (Refs.118,119) suffocation (Ref.120), ground water degradation affecting acidity, alkalinity and hardness (Refs.121,122), destruction of vegetation (Ref.123), and discharge of microorganisms (Ref.122). Consequently a great deal of research on the production of gases and leachates from decomposing refuse has been carried out with the objective of identifying methods for their control.

A pattern of biogas production in relation to the age of a landfill has been categorized into four phases (Refs.123a,124). The initial aerobic phase is short, leading into the second phase of high carbon dioxide production at approximately a molar equivalent to the oxygen consumed so that little nitrogen is displaced. In the anaerobic non-methanogenic phase, a carbon dioxide "bloom" occurs as organic acid production proceeds. These blooms which may produce as much as 90% CO_2 have been reported to occur after 11 days (70% CO_2) and 23 days (50% CO_2) (Ref.125) and after 40 days (90% CO_2) (Ref.126). Hydrogen production increases and nitrogen displacement usually increases dramatically. In the third phase, methanogenesis activity begins and methane concentrations increase as carbon dioxide and hydrogen levels decrease. This steady-state phase has been found to occur as early as 180 days after filling operations began (Ref.127), 250 days (Ref.128) or as late as 500 days (Ref. 126). The fourth steady-state phase of methane production occurs considerably later and ranges from 50 - 70% CH_4 (Refs.126,127, 129). Pretreatment operations which affect the rate of gas production in landfills, such as particle size reduction, classification and alakaline pretreatment, are discussed in Section 3. These operations are performed before deposition of the organic matter into the landfill to control physical and chemical reactions taking place within the system.

It has recently been proposed that enhancement of microbial activity can be achieved by recycling leachate through the decomposing refuse. The leachate which accumulates along an impermeable barrier, such as a clay substratum, is collected and recycled with the refuse cells. A comprehensive laboratory study of this technique began in 1971 at the Georgia Institute of Technology under the direction of Dr. Fred Pohland, for the purpose of accelerating pollutants from the leachate (Ref. 130). Recirculated leachate was pumped back through the fill and allowed to percolate through the refuse. After 11 weeks refuse removed from the fill indicated that decomposition had proceeded at a more rapid pace in the fill receiving recycled leachate than in the control fill where the leachate was wasted. Carbon reduction and volatile solids reduction was greater in the experimental fill than in the control (Ref. 131).

The economic success of gas extraction from existing landfills has led to current interest in increasing landfill gas yields from municipal solid wastes and other sources of biomass. Attempts are being made to accelerate biodegradation rates of landfill wastes and hence, gas production rates, by pretreating the refuse before deposition into the landfill, and enhancing microbial metabolism during decomposition. The concept of a "controlled landfill" implies construction and daily operation of the landfill for the purpose of attaining high methane yields. This "controlled landfill" technique incorporates an admixture of nutrients, buffer, and inoculum with the biomass source (Ref.132). Recent laboratory scale experiments with municipal solid waste mixed with digested sewage sludge (inoculum and nutrient supply) and buffer have resulted in approximately 60% biomass conversion after 6 months at mesophilic conditions (Ref. 133). Jewell <u>et al.</u> (Ref.114) have shown similar results with wheat straw mixed with digested dairy manure effluent and utilizing leachate recycle. These results were at mesophilic conditions, with 20% solids and approximately 15 lb/ft^3 density of solids in the reactor.

The results with the "controlled landfill" concept with both municipal solid waste and wheat straw indicate the potential of the process. However, additional experimentation is necessary to determine the kinetics of high solids digestion.

4.2.1 Kinetics of Batch Digestion

The rate of substrate removal in a digestion process is assumed to be given by Eq. (4.1). This is applicable to both batch and continuous processes. For a batch process the substrate concentration after time , t, is given by

$$C_B = C_{Bo} \exp(-k\tau) \qquad (4.9)$$

and the total gas production is given by

$$G_{Batch,\ total} = AC_{Bo}[1-\exp(-k\tau)] \qquad (4.10)$$

where A is the gas produced per mass of biomass converted. This is the same for the plug flow system. The rate of gas production, VVD, found from the derivative of Eq. 4.10, decreases with time and is proportional to $e^{-k\tau}$ (this is the same as Eq. 4.7). Experimental results indicate that there is first an increase of gas production rate with time followed by a decrease. This difference between practice and theory is due to the assumption of first order kinetics for the theory. This assumes that the microorganism level, volatile acid concentration, pH, nutrients, and other digestion conditions are at the appropriate level for first order kinetics to be applicable. In practice, it is difficult for such a batch experiment to be established at initiation, and therefore a time delay and lower gas production are observed initially.

Another important aspect of the theory is determination of the rate constant, k, as discussed in Section 4.1.1. For high solids digestion, it is expected that the type of relationship presented in Eq. 4.8 will still be valid, incorporating the same activation energy, E, but with a lower value for k_o. Data are not available for determination of E and k_o for high solids digestion of crop residues at various temperatures.

The need of such data is readily apparent for system design. Most experimental results for high solids digestion were presented for constant temperature from initiation to completion. In practice, however, a landfill system will start at ambient temperature and will increase in temperature due to heat of reaction associated with methane production. This increased temperature will then give a higher rate of gas production. This temperature-gas production change with time needs to be determined in more detail.

4.2.2 Consideration of Thermal Effects in Landfills

It is to be expected that crop residues will be landfilled at ambient temperature. If this temperature is 55°F ("cave temperature") and the residue remains at this temperature, digestion rate at an activation energy, E_a, of 15 kcal will be 13% of that at 98°F. This would imply a stabilization time requirement of at least 10-15 years for digestion of the fill material based on experience with municipal solid waste. This assumes that the methane evolution profile of filled material is the same as that for the tested municipal solid waste, and that the ultimate yield [3.10 ft^3 (STP)/lb volatile solids] is the same as that for tested municipal solid waste.

However, methanogenesis is exothermic and advantage may be taken of the heat of methanogenesis which will warm up the landfill, substantially accelerating digestion. The heat of methanogenesis is about 13 kcal/g mol (65 Btu/SCF CH_4). Although low, this heat is significant. The heat evolved will warm up the fill material and be lost by water evaporation, a minor consideration below 120°F, and by conduction to the environment.

Some estimates of the magnitude of the contribution of the heat of methanation may be made based on likely values for fill thermal conductivity, heat capacity, thermal conductivity and heat capacity of the environment (including surrounding soil), and fill geometry. Fill geometry must be such that heat loss by conduction is minimized and heat retention by the fill is maximized. Heat loss due to convection associated with evaporated water and product gas leaving is unavoidable. It is to be noted that the purpose of these calculations are useful in determining how large and deep the fill must be to give valid operating data.

It is further assumed that the fill has a content of 25% solids by weight. Since over half is water (k = 0.33 Btu/ft.hr.°F), but some voids will be present, k is estimated at 0.25 Btu/ft.hr.°F or 6 Btu/ft.day°F. The conductivity is not likely to be much higher, but could be considerably lower with a significant void fraction.

The steady state fill temperature in the center of the fill may be computed as a function of depth, assuming no edge effects and that the top and bottom of the fill are at ambient temperature, as follows (Ref.134):

$$T_F - T_A = \frac{\dot{Q}}{2k}\left[\frac{D}{2}\right]^2$$

where $\dot{Q}$ = rate of heat generation, 65 $\dot{R}$ Btu/ft^3 reactor/day

D = depth of fill, feet

k = thermal conductivity of fill, Btu/ft day °F

$T_F - T_A$ = temperature of fill center above ambient

$\dot{R}$ = methane production rate, VVD

Thus, it may be calculated for a 10 foot deep fill and $\dot{R} = 0.128$,

$$\Delta T = \frac{0.128\ (65)}{6}(25) = 17°F$$

This calculation indicates that the fill center at steady-state will be 17 °F above ambient; an alternative way of expressing the result is that if the fill center were 17 °F above ambient with $\dot{R} = 0.128$ VVD ($\dot{Q} = 8.33$ Btu/ft^3 day), all heat generated will be lost to the surroundings leaving no heat available to further warm the fill. Also,as digestion rate slows with increasing conversion, heat will leak rapidly and fill temperature would be expected to trend toward ambient.

For a 20-foot deep fill, the same calculation shows that $\Delta T =$ 70°F. The fill will not usually reach such a temperature before digestion is completed. Placing this result in another perspective, 50% of the heat of the methanogenesis would be lost if in the center of the fill were 30°F above ambient and the surface uninsulated. The balance of the heat would be available to further warm the fill.

The effect of conduction from the top and bottom of the fill should be considered. Clearly, the top surface of the fill will be at ambient temperature if there is no insulation except a thin gas-impermeable membrane. If, however, the fill is covered with loose sand or earth ($k \approx 3$ Btu/day·ft·°F) to a depth of 2 feet to give $h = 1.5$ Btu/ft^2·day°F, the heat loss from the surface insulation may be substantially reduced. If, as in the previous example $\dot{Q} = 8.3$ Btu/ft^3 day and the half-cell depth is 10 feet ($D \simeq 20$), the supportable ΔT across the sand insulation will be 60°F. This surface layer conductance is 0.67 ft^2°F day/Btu. Heat loss through the earth underlying the fill may be estimated to a first approximation by heat transfer to a flat plane of infinite depth having average properties of the earth's surface after it is subjected to a step change (this calculation is also approximate), as follows (Ref. 134):

$$\frac{Q}{A} = \frac{k\Delta T}{\sqrt{\pi\alpha\theta}} \quad \text{or} \quad h = \frac{k}{\sqrt{\pi\alpha\theta}}$$

where: k = 23 Btu/ft day°F (average of earth's crust)

ΔT = temperature difference between fill and bulk earth

α = thermal diffusivity, k/c_p for earth's crust = 0.46 ft^2/day

θ = time, days

From this it may be calculated that:

$$h = 17\theta^{-\frac{1}{2}}$$

The value for h with this approximation will be time-dependent; at 30 days, $h = 3.2$ Btu/ft^{2}day°F and at 180 days, $h = 1.27$ Btu/ft^{2}F day. This calculation simply indicates that loss through the bottom of the fill is of the same order as through the top over gas production durations of a few months to a few years. Taking into account the thermal resistance of the top of a covered (uninsulated) fill, resistance of the underlying earth, and of the fill itself, these calculations suggest that for a 20 foot deep fill whose center is 35°F above ambient, less than 15% of the heat generated will be lost to the environment.

It is clear that the top of the fill should be insulated in order to ensure that filled material does not cool near the surface and require an unacceptably long time for digestion. Typical earth at the bottom of the fill will act as an effective insulator. It is also clear that the fill should be large and deep in order to take practical advantage of the warming due to methanogenesis to accelerate the reaction. Given the uncertainty at this stage in values to use for thermal conductivity of fill material as well as losses through fill faces, it is only possible to state that it appears that the depth of fill should be at least 20 feet. It is clear that the heat of reaction is more completely retained the deeper the fill; in fact, conditions at mid-depth in the fill deviate from adiabatic (i.e., tend toward the temperature of the surroundings) approximately inversely as the square of the fill depth. A further consideration is that the fill should be of large area, say 100 x 100 feet, to minimize side or edge effects. This complex situation can be modeled much more exactly with knowledge of correct values of relevant parameters and detailed thermal modeling procedures.

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Section 5
BASIS OF ECONOMIC ANALYSIS

To ensure an objective and equitable economic evaluation of the various processes analyzed in this program, a consistent and uniform set of cost estimating criteria must be applied. Commonly used methods for profitability evaluation include rate of return on investment, discounted cash flow, present worth, and payout period. Another method which has been used previously by Dynatech R/D Company is the utility financing method, which is applicable to a specific set of conditions. Each of these methods necessitates accurate predictions of total investment and profits.

5.1 Cost Escalation Index

Capital cost estimates used in this study were based on price levels at March 1979. Cost data were obtained from manufacturers' quotes, the literature, empirical cost correlations, and various other sources. The last three categories present costs which are often based on price levels at some time in the past. These data must be updated to present costs before they can be used to provide a reliable analysis. This can be done by the use of a cost index. Current costs can be determined by multiplying the original cost by the ratio of the present index value of the time when the original cost was obtained.

The index used in this study is the Chemical Engineering (CE) Plant Cost Index (Ref. 135). The composite CE Plant Cost Index is based on nationally averaged costs for equipment, machinery, supports, labor, buildings, engineering and supervision. It is commonly accepted and used in the chemical industry. Based on a value of 100 for 1957-59, the composite CE plant cost index for the base time frame of March 1979 is 232.

5.2 Equipment Cost by Scaling

Digestion systems for processing various feed stream sizes were studied in this project. In most instances it was necessary to estimate the cost based on data for similar equipment with a different capacity. A commonly used scaling relationship for the estimation of equipment cost is the power factor rule (Ref. 136).

$$\text{Cost of equip. a} = \text{cost of equip. b}\left[\frac{\text{capacity of equip. a}}{\text{capacity of equip. b}}\right]^{x} \quad (5.1)$$

where the scaling factor x is a constant. The value of the scaling factor can vary from less than 0.2 to greater than 1.0 depending on the type of equipment being scaled. In the absence of other information, it is common practice to assume a rule-of-thumb value of 0.6 for the scaling factor. In this study, the power factor rule was used when necessary for estimating equipment costs based on scaling factors considered to be most suitable for the particular equipment being considered.

5.3 Comparative Investment Evaluation

In order to compare the various processes considered in this study, it is essential to have a consistent procedure to determine total plant investment, operating costs, and profits, regardless of the comparative method of evaluation.

5.3.1 Capital Cost

The procedure for calculating the total plant investment is outlined in Table 5.1. Capital requirements include all installed onsite plant sections, supporting facilities, contractor's overhead and profits, engineering and design, and project contingency. No land acquisition cost was included in the calculation of total plant investment. The different components of the total plant investment are discussed below.

Table 5.1

BASIS FOR CALCULATING TOTAL CAPITAL REQUIREMENT

Capital Investment		
All Onsite Plant Sections Installed		XXX
Supporting Facilities	5% of All Pl. Sec.	XXX
Total Capital Investment		XXXX
Contractor's Overhead & Profits	10% of Tot. Cap. Inv.	XXX
Engineering and Design	5% of Tot. Cap. Inv.	XXX
Subtotal Plant Investment		XXXXX
Project Contingency	15% of Sub. Pl. Inv.	XXXX
Total Plant Investment		XXXXX

Onsite Plant Sections

Costs for all onsite plant sections include process equipment delivered, piping, instrumentation, and installation. Capital costs for pumping and materials handling were found to be about 5% of the total equipment cost for a typical stirred tank anaerobic digestion process (Ref. 116). This fraction has been assumed for this analysis. The cost for piping, electrical, and instrumentation was estimated to be about 4% of the installed equipment cost.

Supporting Facilities

Supporting facilities include equipment for the generation and distribution of power, waste disposal, storage, fire-protection, landscaping, fencing, painting, maintenance and office equipment, outdoor and indoor lighting, communication equipment, and other miscellaneous service items. Most of these items represent incremental addition to supporting facilities required for the operation of the overall fuel gas production plant. It was estimated that supporting facilities require about 5% of the cost of all installed plant sections.

Contractor's Overhead and Profits

Contractor's fees were assumed to amount to 10% of total capital investment. This includes overhead such as field and home office setups during construction, supervision, construction coordination and engineering, insurance, taxes, and other indirect expenses incurred by the contractor as well as the necessary profit for assuming the risks and responsibilities involved.

Engineering and Design

This component of the capital requirement includes the costs for construction design and engineering, drafting, purchasing, accounting, construction and cost engineering, and general overhead involved in the preparation of construction plans and specifications. An allowance of 5 percent of the total direct costs of the process plant was used for engineering and design services (Ref. 136).

Project Contingency

Contingency funds are usually included in the estimate of total capital requirement. In addition to counterbalancing possible errors in estimation, contingency funds are necessary to compensate for unforseen expenses such as additional pollution control equipment due to change in regulatory rulings, small design changes, unexpected delays, sudden price changes, and others. Contingency usually does not include regular cost escalation due to inflation. In this study, an allowance of 15 percent of subtotal plant investment (see Table 5.1) was included for contingencies.

5.3.2 Operating Costs

The procedure for determining the annual net operating costs is outlined in Table 5.2. Operating costs are expenses incurred directly by the operation of the plant. These expenses are usually calculated on an annual basis and include production materials, purchased utilities, labor, administration and overhead, supplies, local taxes and insurance, and credit for any valuable by-product. A service factor of 90% was used in calculating all operating expenses with the exception of process operating labor, for which a 100% service factor was used. Each of the operating cost items is briefly discussed below.

Production Materials

Production materials include raw materials and replacement for expendable supplies necessary for the normal operation of the facility. The primary raw material for the digestion system is the raw feed. Other production materials include chemicals for pretreatment.

Table 5.2

BASIS FOR CALCULATING NET OPERATING COSTS

Production Materials	XXX
Purchased Utilities	
Electric Power	XXX
Steam	XXX
Labor	
Process Operating	XXX
Maintenance	XXX
Supervision	XXX
Administration and Overhead	XXX
Supplies	
Operating	XXX
Maintenance	XXX
Local Taxes and Insurance	XXX
Total Gross Operating Cost	XXXXX
Penalties for Effluent Treatment/Disposal	XXXX
Credit for By-Product	(XXXX)
Total Net Operating Cost	XXXXX

Purchased Utilities

Utilities requirements for digestion processes include electric power and steam. Process water and cooling water could also be required. The cost of these utilities usually varies widely depending upon the amount of consumption, plant location, and source.

Labor

Manpower required for the normal operation of a digestion facility is dependent on the size of the facility and includes process operating, maintenance, and supervisory labor. Maintenance labor requirement is related to the scale and complexity of the operation. For large systems an allowance of 1.5 percent of total plant investment for maintenance labor was assumed.

The amount of supervisory labor needed is related to the operating and maintenance labor requirement and scale of the system. Cost of supervisory labor was estimated to be 15 percent of operating and maintenance labor for large digestion systems.

Administration and Overhead

This item of costs involves indirect operating expenses that are required for routine large plant operation. These expenses include executive and clerical support as well as general overhead expenditures such as medical services, general engineering, safety services, employee benefits, control laboratories, janitorial services, shops, communications, receiving facilities, etc. Administrative and overhead costs were estimated to amount to 60 percent of total labor requirements.

Supplies

Replenishment of expendable supplies are necessary to maintain normal operation of the plant. Operating and maintenance supplies include miscellaneous items such as charts, lubricants, janitorial supplies, test chemicals, etc. The cost of operating supplies was assumed to be 30 percent of process operating labor while maintenance supplies were estimated to be 1.5 percent of total plant investment.

Local Taxes and Insurance

Local taxes and insurance are charges with magnitudes which vary with the type and location of operation. They were estimated to amount to 2.7 percent of total plant investment for gas treatment systems.

Credits/Penalties

Credits for recovery of the digester effluent, and possibly the acid gas stream, could be significant and might alter the economics of the entire operation. Penalties are associated with effluent treatment or disposal.

5.3.3 Discounted Cash Flow Method

The discounted cash flow method (Ref. 136) is one technique which can be used to evaluate the various processing alternatives considered in this study. This method is based on the time value of money and utilizes discounted annual cash flows with a return on investment. The discounted cash flow method determines the rate of return to provide zero present worth. This differs from the present worth method which determines the present value for a specified return on investment.

In order to calculate the present worth of a process the annual cash flows (including initial costs for plant investment for year 0) are multiplied by discount factors (which are tabulated or can be calculated) with the sum of the products equal to the present worth,

$$PW = \sum_{j=0}^{n} C_j d_j \qquad (5.2)$$

where PW is the present worth, C_j is the annual cash flow for year j, n is the expected life of the system, and d_j is the corresponding discount factor defined by

$$d_j = e^{-rj} \tag{5.3}$$

where r is the expected rate of return. This relationship assumes continuous compounding. If annual compounding were utilized, the discount factor, d'_j, would be

$$d'_j = 1/(1 + r)^j \tag{5.4}$$

The discount factors for continous compounding are lower than for annual compounding and therefore use of d_j would give a lower present worth than use of d'_j.

Calculation of annual cash flow includes contributions for gross revenue, operating costs, depreciation, and taxes. Gross revenue is the value of energy and other products produced in the digestion process. Operating costs are the process costs indicated in Table 5.2. Depreciation is a function of the plant life and total plant investment. Federal taxes are determined from the taxable income. A procedure for calculation of annual cash flow is presented in Table 5.3.

Another method of using discounted cash flow is to assume an expected rate of return on investment and determine the unit gas cost which will give a present value of zero for that rate of return. This procedure will be utilized in the analysis to determine unit gas cost for each system design as a function of expected rate of return on investment.

It should be noted that this procedure only compares rate of return and unit gas cost and gives no indication of the magnitude of investment or revenues. These factors are important in determining which system should be considered.

Table 5.3

ANNUAL CASH FLOW

1.	Gross Revenue	XXXX
2.	Operating Costs	- XXX
3.	Gross Profit (1-2)	XXXX
4.	Depreciation (Tot. Plant Investment/Plant Life)	- XXX
5.	Taxable Income (3-4)	XXXX
6.	Federal Tax (tax rate x 5)	- XXX
7.	After-Tax Income (5-6)	XXXX
8.	Annual Cash Flow (7+4)	XXXX

Table 5.4

GAS COST CALCULATION PROCEDURE
UTILITY FINANCING METHOD*

Basis:

- 20-year project life
- 5%/year straight line depreciation on Total Capital Requirement excluding Working Capital

Essential Input Parameters:

- Debt/equity ratio used to split Total Capital Requirement
- Percent interest on debt
- Percent return on equity
- Federal income tax rate

Derived Parameters:

- Rate Base = Total Capital Requirement less Accrued Depreciation (includes ½ depreciation for given year)
- Percent Return on Rate Base = Fraction Debt × Percent Interest + Fraction Equity × Percent Return on Equity

Calculated Cash Flows in Given Year:

- Return on Rate Base = Rate Base × (Percent Return on Rate Base ÷ 100)
- Return on Equity = (Fraction Equity × Rate Base) × (Percent Return on Equity ÷ 100)
- Federal Income Tax = Return on Equity × (Percent Tax Rate ÷ [100 - Percent Tax Rate])
- Depreciation = 0.05 × (Total Capital Requirement - Working Capital)
- Total Gas Revenue Requirement in Given Year = Return on Rate Base + Federal Income Tax + Depreciation** + Total Net Operating Cost

Gas Costs:

- In given year: Total Gas Revenue Requirement ÷ Annual Gas Production
- 20-year average: Total Gas Revenue Requirement Over Project Life ÷ (20 × Annual Gas Production)

Notes:

* AGA Method as modified by Panhandle-Eastern Pipeline Company and used by Synthetic Gas-Coal Task Force

**Depreciation is split according to the debt/equity ratio and used to pay back debt and equity in annual installments. (Working capital is used to offset unpaid debt and equity at the end of the project life.)

5.3.4 Utility Financing Method

The procedure for calculating the unit gas cost based on the utility financing method used by the American Gas Association (Ref. 137) is outlined in Table 5.4. This procedure was described in a report from Esso Research and Engineering Company to the Federal Power Commision (Ref. 138). The average unit gas cost based on this method is given by

$$UGC = \frac{N + 0.05\ (C - W) + 0.5[p' + \frac{t}{1 - t}\ (1 - d)r]\ (C + W)}{G_y} \qquad (5.5)$$

where N = total annual operating cost, \$
C = total capital requirement, \$
W = working capital, \$
p' = fractional return on rate base [$p' = di + (1 - d)r$]
t = fractional federal income tax rate
d = fraction debt
r = fractional return on equity
i = fractional interest on debt
G_y = annual gas production, MMBTU/year
UGC = unit gas cost, \$/MMBTU

The first term on the right side corresponds to the net operating cost, the second term is due to 5 percent per year straight-line depreciation, and the third term accounts for the return on rate base as well as federal income tax. The sum of these terms gives the total average annual revenue requirement. The unit gas cost is obtained by dividing the average annual revenue requirement by the annual gas production. No escalation of operating cost during the life of the project was assumed.

The following bases were used in this study:

Debt/equity ratio = 75%/25%
Percent interest on debt = 10%
Percent return on equity = 15%

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Section 6
BASE LINE SYSTEMS ANALYSIS

One approach to systems analysis of engineering processes is to establish a base case for which the economic analysis is performed. This would then be followed by a sensitivity analysis to determine the effects of changes in the various system parameters. The procedure in this study is more complicated because of the many potential base cases, resulting in the selection of nine base line systems. These systems were chosen to include the different types of available residues and the three significantly different scales of operation, namely, small farm, cooperative, and utility/industrial sizes. The conditions for these base line cases are presented in this section, followed by the analysis of the sytems. The sensitivity analysis is discussed in Section 7.

6.1 Crop Residues

The summary of agricultural data presented in Section 2 indicates that there are three major crop residues which should be considered, namely, small grain straws (primarily wheat straw), corn stover, and large grain straws (rice). These choices were based on the total U.S. residue available and on localized conditions of high residue concentration, e.g., rice straw in the Sacramento River Valley of California.

The per acre yield for these residues are estimated from the results in Section 2 to be 1.6, 1.75, and 2.3 tons/acre, respectively. The composition of these residues utilized in the analysis are presented in Table 6.1.

Table 6.1

Residue Composition

	Wheat Straw	Corn Stover	Rice Straw
% Solids Content	90	50	92.5
% Volatile Solids	94	95	83
% Biodegradability (of Volatile Solids)	42	36	50

6.2 System Size

In this analysis, base line conditions were established for small, medium, and large scale processes. By small scale is meant a process designed for use on a small farm, utilizing the residue produced on that farm. The medium scale system would be a cooperative venture, designed to utilize the residue from 100 small farms (two orders of magnitude greater than the small farm system). The large scale system is an order of magnitude greater than the medium size, utilizing residue from 1000 farms. This would be a size sufficiently large for a utility or industrial complex.

The average size of a small farm in the U.S. is approximately 400 acres (Table 2.12). The three different sizes will utilize residues from 400, 40,000, and 400,000 acres for the small, medium, and large scale systems. The capacities of the systems, obtained by multiplying the acreage by the yields are presented in Table 6.2 for each crop residue considered. The values presented are tons/day, assuming 365 days per year operation.

These nine cases presented in Table 6.2 are the base line cases utilized in this analysis. A discussion of the other system variables is presented in the following sections.

Table 6.2

System Capacities
(tons/day)

	Wheat Straw	Corn Stover	Rice Straw
Small (400 acres)	1.75	2	2.5
Medium (40,000 acres)	175	200	250
Large (400,000)	1,750	2,000	2,500

6.3 Method of Cost Analysis

The cost analysis methods are discussed in Section 5. The type of routine will be dependent on system size. The utility financing method of cost analysis will be utilized only to determine the unit gas cost for the large scale system. The discounted cash flow (DCF) method will also be utilized for the large scale system to determine unit gas costs for several different returns on investment. The DCF method will be used for the small and medium scale systems.

6.4 Process Options

The various process options utilized for each base line system are presented in Table 6.3. The options considered are the same for each scale and crop residue considered. Differences in operating conditions are discussed below.

6.4.1 Digestion

The digestion process incorporated into the base-line designs is the CSTR, because it is the process with most available performance data (but with other substrates). The batch digestion process utilizing the "controlled landfill" technique for enhanced gas production is less developed than the continuous process and will be analyzed in the sensitivity analysis.

The conditions for digestion are presented in Table 6.4. In all cases, it is assumed that manure is added with the crop residue (in the ratio of 1 part manure solids/10 parts feed solids) to provide nutrients and inoculum.

Table 6.3

Base Line Process Options

	Small Scale	Medium Scale	Large Scale
Storage	Y	Y	Y
Shredder	Y	Y	Y
Holding/Mixing	Y	Y	Y
Pretreatment	N	N	N
Digestion	C	C	C
Heat Exchange	Y	Y	Y
Dewatering	N	N	N
Gas Purification	N	N	N

Y = option used

N = option not used

C = CSTR digester

The major difference between the small scale and the other two sizes is the digestion temperature and retention time. The medium and large scale systems utilize thermophilic conditions, 60°C, with a retention time of 10 days. The small scale system incorporates a mesophilic temperature of 35°C with a 16-day retention time. The major reason for this is the small farm system should be less complicated due to the possibility that the farmer does not have sufficient time to operate a complicated process. The medium and large scale operations require technically trained operators.

Table 6.4

Base Line Digestion Conditions

	Small Scale	Medium Scale	Large Scale
Digester Temperature (°C)	35	60	60
Retention Time (days)	16	10	10
Solids Concentration (%)	10	10	10

The digester feed solids concentration is assumed to be 10% for all cases. High solids concentration is preferred since it results in smaller reactor volume and lower effluent stream heat losses, both factors contributing to lower costs. Higher solids continuous digestion (up to 17%) has been obtained with other substrates, such as dairy cow manure (Ref. 139). However, Pfeffer and Quindry (Ref. 112) have indicated some difficulty in digester mixing of corn stover with solids content above 8%. A value of 10% solids is utilized for feed concentration to ensure that the digester solids concentrating will be less than 8%. Note that with effective pretreatment, a 10% feed concentration would result in significantly less than 8% digester solids and could justify use of higher feed solids with an associated reduction in digester size and costs.

6.4.2 Storage

Storage of crop residue is necessary for continuous digestion processing. The residue is a seasonal source and therefore must be stored after collection and delivery to the digester facility and prior to processing. The residence time for storage has been assumed to be 12 months. It is possible that residue could be stored in stacked bales or bunker silos without significant degradation (except in the top layer of residue).

6.4.3 Shredder

A shredder is included in the base line design in order to provide comminution of the crop residue to an easily handled size.

6.4.4 Pretreatment

Pretreatment was not included in the base line design. A detailed discussion of pretreatment is included in the sensitivity analysis presented in Section 7.

6.4.5 Heat Exchange

A heat exchanger is provided in the base design to recover the sensible heat of the digester effluent stream.

6.4.6 Dewatering

Dewatering was not include in the base line design, but is included in instances of digester effluent solids recovery, discussed in Section 7.

6.4.7 Gas Purification

The base line systems did not include gas purification. This option is included only for the large utility/industrial scale process when gas cleanup is required for delivery into a pipeline, as discussed in Section 7.

6.5 Labor

The labor requirements and costs for the base line designs will significantly affect the annual operating costs. The values utilized are presented in Table 6.5.

Table 6.5

Labor Allocation

	Small Scale	Medium Scale	Large Scale
Men Per Shift	1	4	8
Hours Per Shift	2	8	8
Shifts Per Day	1	3	3
Hourly Wage ($)	0	6	6

The effect of variation in labor allocation will be discussed in Section 7.

For the small scale system, it is assumed that the process will require 2 hours per day of the farmer's time, but the value of this time was taken to be $0/hr. The cost of maintenance labor for the small scale operation was also taken as $0/hr. There was also no supervision, overhead, or administration cost attributed to the small scale base line design.

6.6 Crop Residue Cost

The cost of crop residue will significantly affect the economics of the conversion process. For all base line cases, the value of this crop residue was taken to be $0/ton. A detailed discussion of the effect of residue cost is presented in the sensitivity analysis in Section 7.

6.7 Credits/Penalities

Significant credits or penalties can be attributed to the digester effluent system, e.g., credit for fertilizer or refeed value. However, for the base line system, the credits and penalties are disregarded. A detailed discussion of these factors is included in the sensitivity analysis presented in Section 7.

6.8 Other Base Line System Parameters

The value of the other parameters used in the base line analyses are presented in Table 6.6.

6.9 Base Line Systems Results

The results for the base line systems analyses are presented in Figures 6.1, 6.2, and 6.3 for corn stover, rice straw and wheat straw, respectively. The details of the analyses are presented in Tables 6.7 - 6.15. It is apparent from these results that there is an economy of scale, i.e., the unit gas cost is lowest for the largest scale system for all crop residues considered.

The results in Figures 6.1, 6.2, and 6.3 indicate unit gas cost as a function of system size utilizing a discounted cash flow method for the returns on investment indicated. For the large scale system, the unit gas cost obtained using the utility financing method is also presented. For each case, the unit gas cost necessary to provide a specified return on investment is higher for higher ROI. Also, the utility financing method results in a lower unit gas cost than for 10% ROI discounted cash flow, even though the return on equity for the utility financing system is 15%. One reason for this is the DCF method incorporates a time value of money by use of discount factors, thus requiring a higher unit gas cost.

There are several significant performance differences between the different size systems. The medium and large scale base line systems incorporate a CSTR at 60°C and 10 days retention, which gives a fractional conversion of

Table 6.6

BASE LINE SYSTEM PARAMETERS

Parameter		Value
A	ft^3 CH_4/lb converted	6.6
AW	Labor cost ($/hr)	See Table 6.5
CEP	Cost of electricity (¢/kwh)	5.0
CF	Heat capacity of digester slurry (Btu/lb°F)	1.0
CONS	Cost constant for equipment	See Appendix A
CRF	Cost of feedstock ($/ton)	0.
CST	Cost of steam ($/MM BTU)	5.0
DIGMC	Digester maximum capcity (ft^3)	100,000
DIGWK	Digester work (HP/ft^3)	0.0002
DIR	Interest on debt (fraction)	0.1
DLIFE	System lifetime (years)	10
DNSDG	Digester slurry density (lb/ft^3)	64
DNSHL	Holding tank contents density (lb/ft^3)	64
DNSTR	Storage contents density (lb/ft^3)	22
DPRC	Rate of depreciation (fraction)	0.05
EA	Activation energy for Arrhenius rate equation (cal/mole)	15180
EFFS	Efficiency of steam utilization (fraction)	0.80
EX	Equipment cost scale exponent	See Appendix A
FBVSF	Fraction of bio.vol. solids in feed volatile solids	See Table 6.1
FBVSM	Fraction of bio. vol. solids in manure	0.6
FD	Residue feed rate (tons/day)	See Table 6.2
FDBT	Fraction debt	0.75
FITR	Federal income tax rate (fraction)	0.48*
FMAN	Ratio of manure solids to residue solids	0.1
FSF	Fraction of solids in feed	See Table 6.1
FSM	Fraction of solids in manure	0.12
FS1	Fraction of solids in holding tank	0.1

Parameter		Value
FS3	Fraction of solids in digester feed	0.1
FVSF	Fraction of volatile solids in feed	See Table 6.1
FVSM	Fraction of volatile solids in manure	0.8
HEXMC	Heat exchanger maximum capacity (ft^2)	10000
HLDMC	Holding tank maximum capacity (ft^3)	300,000
HLDWK	Holding tank work (hp/ft^3)	0.0002
HRTDG	Digester retention time (days)	See Table 6.4
HRTHL	Holding tank retention time (days)	1
HRTST	Storage tank retention time (days)	360
HTC	Heat transfer coefficient in heat exchanger (Btu/hrft^{2}F)	80
OIND	Cost index for year of equipment cost estimation	See Appendix A
OINDX	Current cost index	220.
PAH	Fraction of labor cost for administration and overhead	0.6
PCOP	Fraction of equipment cost for contractor's overhead and profit	0.1
PED	Fraction of equipment cost for engineering and design	0.05
PIDC	Fraction of total plant investment for interest during construction	0.09
PLTI	Fraction of total plant investment for local taxes and insurance	0.027
PM	Fraction of total plant investment for maintenance labor	0.015*
PMM	Fraction of total plant investment for maintenance supplies	0.015*
POPS	Fraction of operating labor cost for operating supplies	0.3*

Parameter		Value
PPC	Fraction of subtotal plant investment for project contingency	0.15
PPMP	Fraction of equipment cost for materials handling equipment	0.05
PSEP	Fraction of equipment cost for electricity and piping	0.04
PSF	Fraction of equipment cost for support facility	0.05
PSUP	Fraction of annual gross operating cost for plant start-up	0.20
PSV	Fraction of labor cost for supervision	0.15*
PWC	Fraction of total plant investment for working capital	0.02
RE	Return on equity	0.15
RKO	Rate equation constant (day^{-1})	3.0×10^9
SHRMC	Shredder maximum capacity (tons/hr)	25.
SHRWK	Shredder work (HP/tons/hr)	15.
STF	Stream factor (fraction of year in operation)	0.9
STRMC	Storage maximum capacity (ft^3)	300000
TA	Ambient temperature (°C)	10.0
TC	Digester temperature (°C	See Table 6.4
TMP	Manpower requirement	See Table 6.5
WD	Hours per work day	Table 6.5

* For the small scale system these factors are 0, except for the tax rate which is taken as 20%.

Fig. 6.1 Unit Gas Cost as a Function of System Capacity

Base Line Systems Analyses for
Corn Stover (——— DCF Method;
⊙ Utility Financing Method)

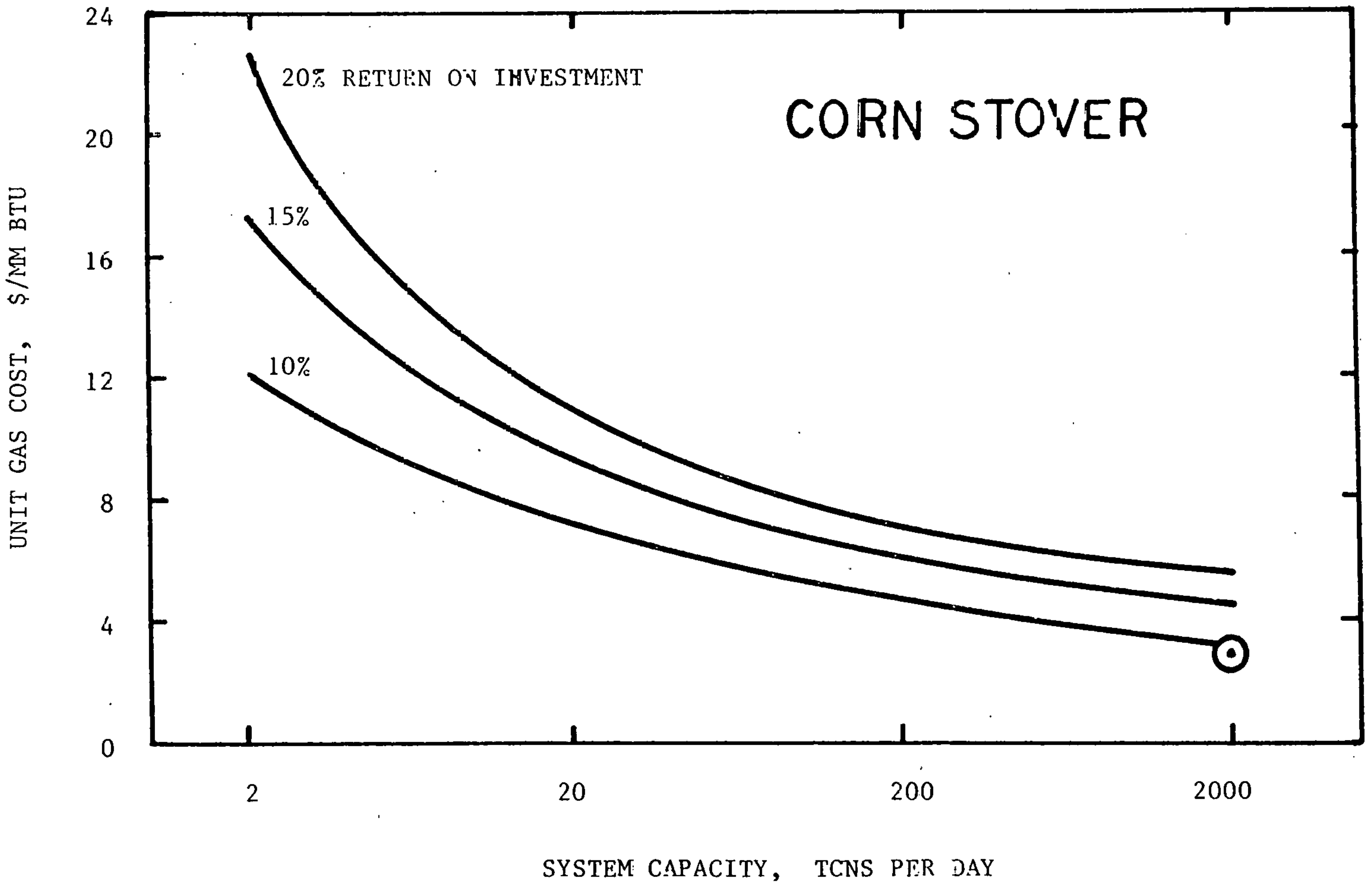


Fig. 6.2 Unit Gas Cost as a Function of System Capacity

Base Line Systems Analyses for
Rice Straw (——— DCF Method;
⊡ Utility Financing Method)

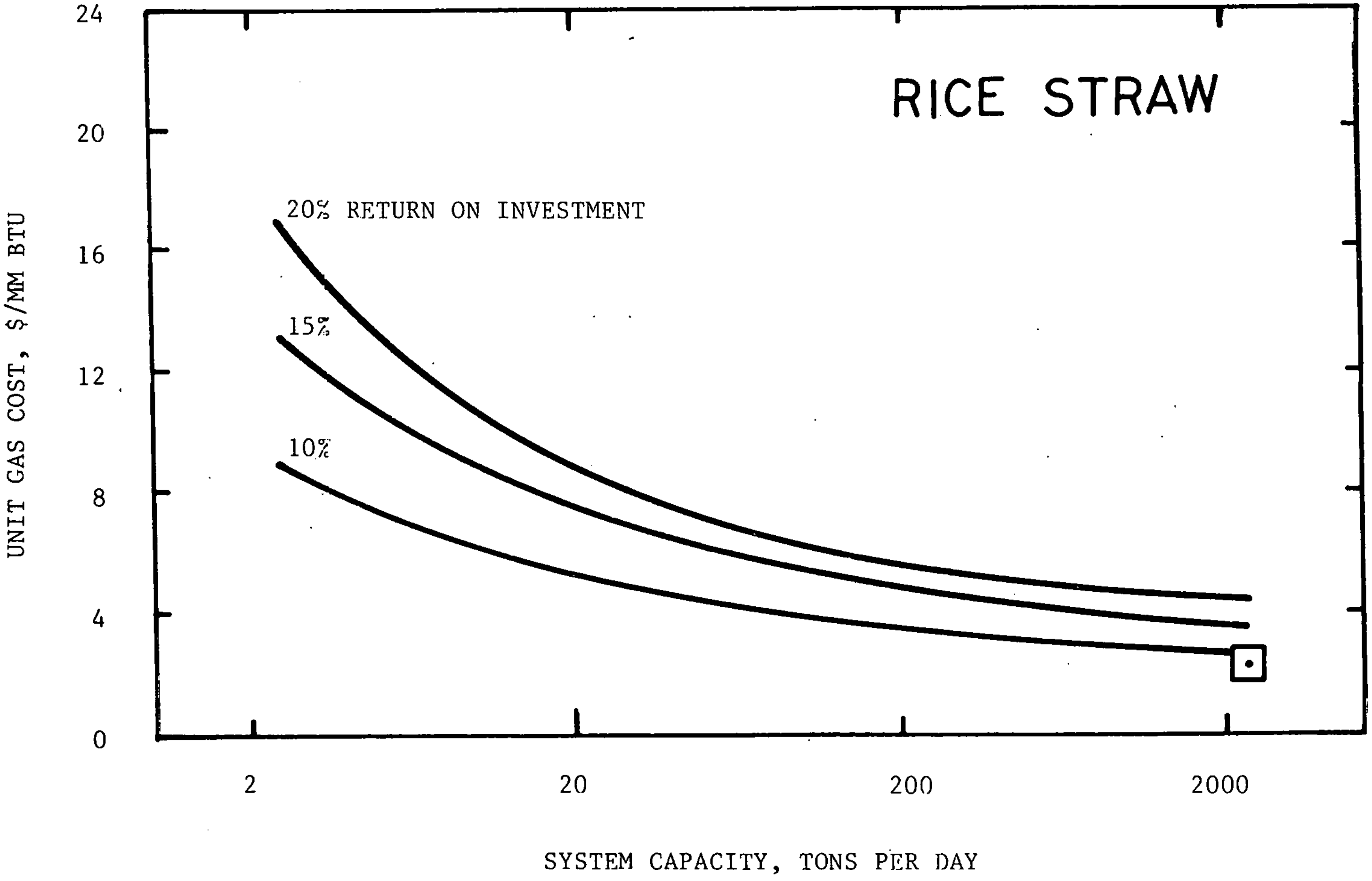


Fig. 6.3 Unit Gas Cost as a Function of System Capacity

Base Line Systems Analyses for
Wheat Straw (——— DCF Method;
△ Utility Financing Method)

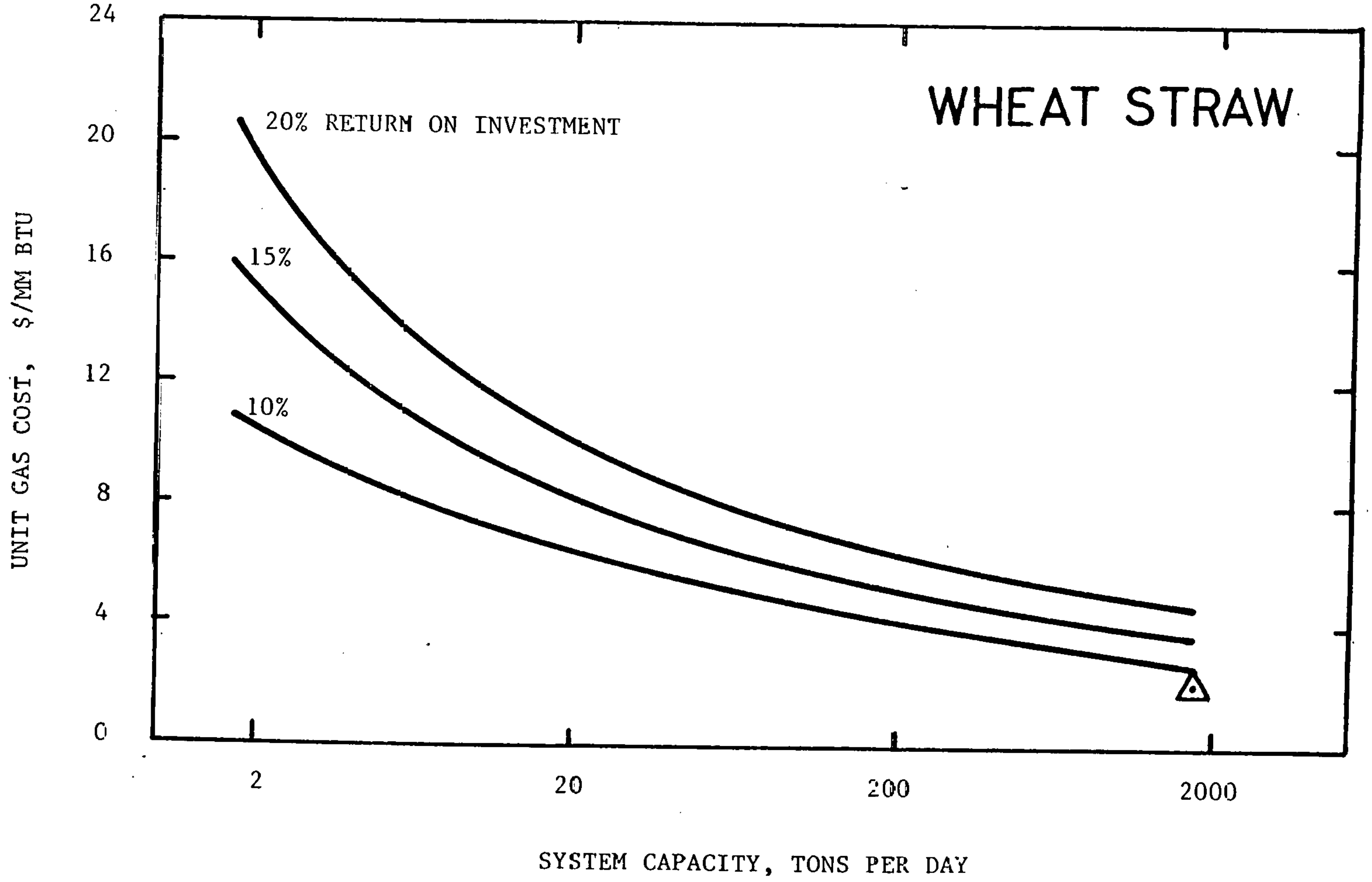


Table 6.7a

```
                    SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                                 2.0  TONS/D
        SOLIDS FRACTION IN FEED                     .500
        VOLATILE SOLIDS FRACTION IN SOLIDS          .950
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL        .360




STORAGE
        NUMBER OF UNITS                            1.
        CAPACITY PER UNIT                      16000. CU.FT.

SHREDDING
        NUMBER OF UNITS                            1.
        CAPACITY PER UNIT                   .1667E+00 TONS/HR
        POWER REQUIREMENT                       .2500E+01 HP

HOLDING-MIXING

        NUMBER OF UNITS                            1.
        CAPACITY PER UNIT                   .6250E+03 CU FT.
        POWER REQUIREMENT                       .1250E+00 HP

PRETREATMENT-NONE USED

DIGESTION

    CSTR
        NUMBER OF UNITS                            1.
        CAPACITY PER UNIT                   .1100E+05 CU.FT.
        DIGESTER TEMPERATURE                     35.C
        RETENTION TIME                           16.0DAYS
        CONVERSION EFFICIENCY                     .451
        POWER REQUIREMENT                         .2200E+01HP

    GAS PRODUCTION                                .425  VVD
                                           .4673E+01  MM BTU/D
    HEAT EXCHANGER
        NUMBER OF UNITS                            1.
        HEAT EXCHANGER AREA                 .2029E+03 SQ.FT.

    TOTAL HEAT REQUIREMENT                  .1124E+01 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.7b

```
                         CAPITAL COST ESTIMATE

                                                  MAY 1979 COSTS ($)


    INSTALLED EQUIPMENT

        STORAGE UNITS                                           1975.
        SHREDDERS                                               1927.
        HOLDING TANKS                                           9185.
        DIGESTERS                                              43219.
        HEAT EXCHANGERS                                         3009.
        MATERIALS HANDLING EQUIPMENT                            2966.
                                                 ---------------------
SUBTOTAL                                                       62281.

     STRUCTURES-ELECT. + PIPING                                 2491.
                                                 ---------------------
SUBTOTAL                                                       64772.

     SUPPORT FACILITIES                                         3239.
                                                 ---------------------
SUBTOTAL CAPITAL INVESTMENT                                    68011.

     CONTRACTOR OVERHEAD + PROFIT                                680.

     ENGINEERING + DESIGN                                       3401.
                                                 ---------------------
SUBTOTAL PLANT INVESTMENT                                      72091.

     PROJECT CONTINGENCY                                       10814.
                                                 ---------------------
TOTAL PLANT INVESTMENT                                         82905.

     INTEREST DURING CONSTRUCTION                               7461.

     START-UP COSTS                                             1193.

     WORKING CAPITAL                                            1658.
                                                 ---------------------
TOTAL CAPITAL REQUIREMENT                                      93217.
```

Table 6.7c

```
                    ANNUAL OPERATING COSTS

                                                   ANNUAL COST ($)


   PRODUCTION MATERIALS

       FEED - $    0.00/TON                                       0.

   UTILITIES

       ELECTRIC - 5.0 CTS./KW-HR                               1418.

       FUEL   -  $ 5.00/MM BTU                                 2307.

   LABOR

       OPERATING LABOR - MEN PER DAY      1.
                         HRS PER SHIFT    8.0
                         HOURLY RATE,  $ 0.00                     0.

       MAINTENANCE LABOR                                          0.

       SUPERVISION                                                0.

   ADMINISTRATION + OVERHEAD                                      0.

   SUPPLIES

       OPERATING                                                  0.

       MAINTENANCE                                                0.

   LOCAL TAXES + INSURANCE                                     2238.
                                           --------------------
GROSS ANNUAL OPERATING COST                                    5963.

   CREDITS/PENALTIES COST                                         0.
                                           --------------------
NET ANNUAL OPERATING COST                                      5963.



             DISCOUNTED CASH FLOW METHOD
  RETURN ON           UNIT GAS COST
  INVESTMENT           ($/MM BTU)

      .10                12.15
      .15                17.44
      .20                22.60
```

Table 6.8a

```
                         SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                                    2.5 TONS/D
        SOLIDS FRACTION IN FEED                        .925
        VOLATILE SOLIDS FRACTION IN SOLIDS             .830
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL           .500




STORAGE
        NUMBER OF UNITS                               1.
        CAPACITY PER UNIT                         20000. CU.FT.

SHREDDING
        NUMBER OF UNITS                               1.
        CAPACITY PER UNIT                      .1126E+00 TONS/HR
        POWER REQUIREMENT                              .1689E+01 HP

HOLDING-MIXING

        NUMBER OF UNITS                               1.
        CAPACITY PER UNIT                      .7813E+03 CU FT.
        POWER REQUIREMENT                              .1563E+00 HP

PRETREATMENT-NONE USED

DIGESTION

    CSTR
        NUMBER OF UNITS                               1.
        CAPACITY PER UNIT                      .1375E+05 CU.FT.
        DIGESTER TEMPERATURE                        35.0
        RETENTION TIME                              16.0DAYS
        CONVERSION EFFICIENCY                          .451
        POWER REQUIREMENT                              .2750E+01HP

    GAS PRODUCTION                                     .505 VVD
                                                .6943E+01 MM BTU/D
    HEAT EXCHANGER
        NUMBER OF UNITS                               1.
        HEAT EXCHANGER AREA                    .2528E+03 SQ.FT.

    TOTAL HEAT REQUIREMENT                     .1274E+01 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.8b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	2228.
SHREDDERS	1482.
HOLDING TANKS	10362.
DIGESTERS	48753.
HEAT EXCHANGERS	3549.
MATERIALS HANDLING EQUIPMENT	3319.
SUBTOTAL	69692.
STRUCTURES-ELECT. + PIPING	2788.
SUBTOTAL	72480.
SUPPORT FACILITIES	3624.
SUBTOTAL CAPITAL INVESTMENT	76104.
CONTRACTOR OVERHEAD + PROFIT	761.
ENGINEERING + DESIGN	3805.
SUBTOTAL PLANT INVESTMENT	80670.
PROJECT CONTINGENCY	12101.
TOTAL PLANT INVESTMENT	92771.
INTEREST DURING CONSTRUCTION	8349.
START-UP COSTS	1278.
WORKING CAPITAL	1855.
TOTAL CAPITAL REQUIREMENT	104253.

Table 6.8c

```
                        ANNUAL OPERATING COSTS

                                                     ANNUAL COST ($)


    PRODUCTION MATERIALS

         FEED - $    0.00/TON                                      0.

    UTILITIES

         ELECTRIC  - 5.0 CTS./KW-HR                             1351.

         FUEL   -   $ 5.00/MM BTU                               2534.

    LABOR

         OPERATING LABOR - MEN PER DAY       1.
                           HRS PER SHIFT     8.0
                           HOURLY RATE    $ 0.00                   0.

         MAINTENANCE LABOR                                         0.

         SUPERVISION                                               0.

    ADMINISTRATION + OVERHEAD                                      0.

    SUPPLIES

         OPERATING                                                 0.

         MAINTENANCE                                               0.

    LOCAL TAXES + INSURANCE                                     2505.
                                                    --------------------
GROSS ANNUAL OPERATING COST                                     6390.

    CREDITS/PENALTIES COST                                         0.
                                                    --------------------
NET ANNUAL OPERATING COST                                       6390.



                DISCOUNTED CASH FLOW METHOD
   RETURN ON              UNIT GAS COST
   INVESTMENT              ($/MM BTU)

       .10                   9.04
       .15                  13.02
       .20                  16.91
```

Table 6.9a

```
                    SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                               1.8 TONS/D
        SOLIDS FRACTION IN FEED                   .900
        VOLATILE SOLIDS FRACTION IN SOLIDS        .940
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL      .420



STORAGE
        NUMBER OF UNITS                          1.
        CAPACITY PER UNIT                    14000. CU.FT.

SHREDDING
        NUMBER OF UNITS                          1.
        CAPACITY PER UNIT                .0102E-01 TONS/HR
        POWER REQUIREMENT                         .1215E+01 HP

HOLDING-MIXING

        NUMBER OF UNITS                          1.
        CAPACITY PER UNIT                .5469E+03 CU FT.
        POWER REQUIREMENT                         .1094E+00 HP

PRETREATMENT-NONE USED

DIGESTION

    CSTR
        NUMBER OF UNITS                          1.
        CAPACITY PER UNIT                .9625E+04 CU.FT.
        DIGESTER TEMPERATURE                   35.0
        RETENTION TIME                         16.0DAYS
        CONVERSION EFFICIENCY                     .451
        POWER REQUIREMENT                         .1925E+01HP

    GAS PRODUCTION                                .483 VVD
                                            .4648E+01 MM BTU/D

    HEAT EXCHANGER
        NUMBER OF UNITS                          1.
        HEAT EXCHANGER AREA              .1771E+03 SQ.FT.

    TOTAL HEAT REQUIREMENT               .9988E+00 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.9b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	1837.
SHREDDERS	1188.
HOLDING TANKS	3546.
DIGESTERS	45212.
HEAT EXCHANGERS	2718.
MATERIALS HANDLING EQUIPMENT	2725.
SUBTOTAL	57227.
STRUCTURES-ELECT. + PIPING	2289.
SUBTOTAL	59516.
SUPPORT FACILITIES	2976.
SUBTOTAL CAPITAL INVESTMENT	62492.
CONTRACTOR OVERHEAD + PROFIT	625.
ENGINEERING + DESIGN	3125.
SUBTOTAL PLANT INVESTMENT	66242.
PROJECT CONTINGENCY	9936.
TOTAL PLANT INVESTMENT	76178.
INTEREST DURING CONSTRUCTION	6856.
START-UP COSTS	1013.
WORKING CAPITAL	1524.
TOTAL CAPITAL REQUIREMENT	85570.

Table 6.9c

```
                        ANNUAL OPERATING COSTS

                                                   ANNUAL COST ($)


    PRODUCTION MATERIALS

         FEED - $    0.00/TON                                    0.

    UTILITIES

         ELECTRIC - 5.0 CTS./KW-HR                             955.

         FUEL   -   $ 5.00/1M BTU                             2051.

    LABOR

         OPERATING LABOR - MEN PER DAY       1.
                           HRS PER SHIFT     8.0
                           HOURLY RATE    $ 0.00                 0.

         MAINTENANCE LABOR                                       0.

         SUPERVISION                                             0.

    ADMINISTRATION + OVERHEAD                                    0.

    SUPPLIES

         OPERATING                                               0.

         MAINTENANCE                                             0.

    LOCAL TAXES + INSURANCE                                   2057.
                                                 -------------------
GROSS ANNUAL OPERATING COST                                   5063.

    CREDITS/PENALTIES COST                                       0.
                                                 -------------------
NET ANNUAL OPERATING COST                                     5063.



               DISCOUNTED CASH FLOW METHOD
   RETURN ON            UNIT GAS COST
   INVESTMENT            ($/MM BTU)

       .10                 10.36
       .15                 15.85
       .20                 20.62
```

Table 6.10a

```
                         SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                                   200.0 TONS/D
        SOLIDS FRACTION IN FEED                         .500
        VOLATILE SOLIDS FRACTION IN SOLIDS              .950
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL            .360



STORAGE
        NUMBER OF UNITS                                6.
        CAPACITY PER UNIT                         266667. CU.FT.

SHREDDING
        NUMBER OF UNITS                                1.
        CAPACITY PER UNIT                       .1667E+02 TONS/HR
        POWER REQUIREMENT                               .2500E+03 HP

HOLDING-MIXING

        NUMBER OF UNITS                                1.
        CAPACITY PER UNIT                       .6250E+05 CU FT.
        POWER REQUIREMENT                               .1250E+02 HP

PRETREATMENT-NONE USED

DIGESTION

    CSTR
        NUMBER OF UNITS                                7.
        CAPACITY PER UNIT                       .9821E+05 CU.FT.
        DIGESTER TEMPERATURE                          60.C
        RETENTION TIME                                10.0DAYS
        CONVERSION EFFICIENCY                           .767
        POWER REQUIREMENT                               .1375E+03HP

    GAS PRODUCTION                                     1.158 VVD
                                                   .7961E+03 MM BTU/D
    HEAT EXCHANGER
        NUMBER OF UNITS                                3.
        HEAT EXCHANGER AREA                     .6673E+04 SQ.FT.

    TOTAL HEAT REQUIREMENT                      .7427E+02 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.10b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	54135.
SHREDDERS	42152.
HOLDING TANKS	110432.
DIGESTERS	986713.
HEAT EXCHANGERS	124000.
MATERIALS HANDLING EQUIPMENT	65872.
SUBTOTAL	1383304.
STRUCTURES-ELECT. + PIPING	55332.
SUBTOTAL	1438636.
SUPPORT FACILITIES	71932.
SUBTOTAL CAPITAL INVESTMENT	1510567.
CONTRACTOR OVERHEAD + PROFIT	15106.
ENGINEERING + DESIGN	75528.
SUBTOTAL PLANT INVESTMENT	1601201.
PROJECT CONTINGENCY	240180.
TOTAL PLANT INVESTMENT	1841382.
INTEREST DURING CONSTRUCTION	165724.
START-UP COSTS	169622.
WORKING CAPITAL	36828.
TOTAL CAPITAL REQUIREMENT	2213555.

Table 6.10c

```
                         ANNUAL OPERATING COSTS

                                                       ANNUAL COST ($)

   PRODUCTION MATERIALS

        FEED - $    0.00/TON                                       0.

   UTILITIES

        ELECTRIC - 5.0 CTS./KW-HR                             117552.

        FUEL   -  $ 5.00/MM BTU                               152482.

   LABOR

        OPERATING LABOR - MEN PER DAY     12.
                          HRS PER SHIFT    8.0
                          HOURLY RATE   $ 6.00                210240.

        MAINTENANCE LABOR                                      27621.

        SUPERVISION                                            35679.

   ADMINISTRATION + OVERHEAD                                  164124.

   SUPPLIES

        OPERATING                                              63072.

        MAINTENANCE                                            27621.

   LOCAL TAXES + INSURANCE                                     49717.
                                                    --------------------
GROSS ANNUAL OPERATING COST                                   848108.

   CREDITS/PENALTIES COST                                          0.
                                                    --------------------
NET ANNUAL OPERATING COST                                     848108.




               DISCOUNTED CASH FLOW METHOD
  RETURN ON           UNIT GAS COST
  INVESTMENT           ($/MM BTU)

     .10                  4.69
     .15                  6.05
     .20                  7.11
```

Table 6.11a

```
                     SYSTEM PERFORMANCE

FEED COMPOSITION

      TOTAL SOLIDS                                250.0 TONS/D
      SOLIDS FRACTION IN FEED                      .925
      VOLATILE SOLIDS FRACTION IN SOLIDS           .833
      BIODEGR. VOL. SOL. FRACT. IN VOL SOL         .500




STORAGE
      NUMBER OF UNITS                             7.
      CAPACITY PER UNIT                       285714. CU.FT.

SHREDDING
      NUMBER OF UNITS                             1.
      CAPACITY PER UNIT                     .1126E+02 TONS/HR
      POWER REQUIREMENT                            .1689E+03 HP

HOLDING-MIXING

      NUMBER OF UNITS                             1.
      CAPACITY PER UNIT                     .7813E+05 CU FT.
      POWER REQUIREMENT                            .1563E+02 HP

PRETREATMENT-NONE USED

DIGESTION

   CSTR
      NUMBER OF UNITS                             9.
      CAPACITY PER UNIT                     .9549E+05 CU.FT.
      DIGESTER TEMPERATURE                      60.C
      RETENTION TIME                            12.0DAYS
      CONVERSION EFFICIENCY                      .767
      POWER REQUIREMENT                          .1719E+03HP

   GAS PRODUCTION                                1.375 VVD
                                          .1181E+04 MM BTU/D
   HEAT EXCHANGER
      NUMBER OF UNITS                             3.
      HEAT EXCHANGER AREA                   .8294E+04 SQ.FT.

   TOTAL HEAT REQUIREMENT                   .8495E+02 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.11b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	65555.
SHREDDERS	32415.
HOLDING TANKS	124573.
DIGESTERS	1249478.
HEAT EXCHANGERS	145968.
MATERIALS HANDLING EQUIPMENT	80899.
SUBTOTAL	1698888.
STRUCTURES-ELECT. + PIPING	67956.
SUBTOTAL	1766844.
SUPPORT FACILITIES	88342.
SUBTOTAL CAPITAL INVESTMENT	1855186.
CONTRACTOR OVERHEAD + PROFIT	18552.
ENGINEERING + DESIGN	92759.
SUBTOTAL PLANT INVESTMENT	1966497.
PROJECT CONTINGENCY	294975.
TOTAL PLANT INVESTMENT	2261472.
INTEREST DURING CONSTRUCTION	203532.
START-UP COSTS	177294.
WORKING CAPITAL	45229.
TOTAL CAPITAL REQUIREMENT	2687528.

Table 6.11c

```
                     ANNUAL OPERATING COSTS

                                              ANNUAL COST ($)

   PRODUCTION MATERIALS

        FEED - $     .  /TON

   UTILITIES

        ELECTRIC - 5.0 CTS./KW-HR                         104745.

        FUEL   -  $ 5.00/MM BTU                           174415.

   LABOR

        OPERATING LABOR - MEN PER DAY     12.
                          HRS PER SHIFT    8.0
                          HOURLY RATE   $ 6.00            210240.

        MAINTENANCE LABOR                                  33922.

        SUPERVISION                                        36624.

   ADMINISTRATION + OVERHEAD                              168472.

   SUPPLIES

        OPERATING                                          63072.

        MAINTENANCE                                        33922.

   LOCAL TAXES + INSURANCE                                 61060.
                                              --------------------
GROSS ANNUAL OPERATING COST                               886472.

   CREDITS/PENALTIES COST                                      0.
                                              --------------------
NET ANNUAL OPERATING COST                                 886472.




              DISCOUNTED CASH FLOW METHOD
  RETURN ON             UNIT GAS COST
  INVESTMENT             ($/MM BTU)

      .10                  3.47
      .15                  4.59
      .20                  5.47
```

Table 6.12a

```
                         SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                                175.0 TONS/D
        SOLIDS FRACTION IN FEED                      .300
        VOLATILE SOLIDS FRACTION IN SOLIDS           .949
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL         .420




STORAGE
        NUMBER OF UNITS                             5.
        CAPACITY PER UNIT                      280000. CU.FT.

SHREDDING
        NUMBER OF UNITS                             1.
        CAPACITY PER UNIT                    .8102E+01 TONS/HR
        POWER REQUIREMENT                      .1215E+03 HP

HOLDING-MIXING

        NUMBER OF UNITS                             1.
        CAPACITY PER UNIT                    .5469E+05 CU FT.
        POWER REQUIREMENT                      .1094E+02 HP

PRETREATMENT-NONE USED

DIGESTION

    CSTR
        NUMBER OF UNITS                             7.
        CAPACITY PER UNIT                    .8594E+05 CU.FT.
        DIGESTER TEMPERATURE                      60.0
        RETENTION TIME                            10.0DAYS
        CONVERSION EFFICIENCY                      .767
        POWER REQUIREMENT                          .1203E+03HP

    GAS PRODUCTION                                 1.315 VVD
                                             .7909E+03 MM BTU/D

    HEAT EXCHANGER
        NUMBER OF UNITS                             2.
        HEAT EXCHANGER AREA                  .8723E+04 SQ.FT.

    TOTAL HEAT REQUIREMENT                   .6343E+02 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.12b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	46317.
SHREDDERS	25997.
HOLDING TANKS	102749.
DIGESTERS	918068.
HEAT EXCHANGERS	101058.
MATERIALS HANDLING EQUIPMENT	59709.
SUBTOTAL	1253899.
STRUCTURES-ELECT. + PIPING	50156.
SUBTOTAL	1304055.
SUPPORT FACILITIES	65203.
SUBTOTAL CAPITAL INVESTMENT	1369258.
CONTRACTOR OVERHEAD + PROFIT	13693.
ENGINEERING + DESIGN	68463.
SUBTOTAL PLANT INVESTMENT	1451414.
PROJECT CONTINGENCY	217712.
TOTAL PLANT INVESTMENT	1669126.
INTEREST DURING CONSTRUCTION	150221.
START-UP COSTS	154120.
WORKING CAPITAL	33383.
TOTAL CAPITAL REQUIREMENT	2006850.

Table 6.12c

```
                      ANNUAL OPERATING COSTS

                                                   ANNUAL COST ($)


    PRODUCTION MATERIALS

        FEED - $   0.00/TON                                      0.

    UTILITIES

        ELECTRIC - 5.0 CTS./KW-HR                            74287.

        FUEL   -   $ 5.00/MM BTU                            130230.

    LABOR

        OPERATING LABOR - MEN PER DAY     12.
                          HRS PER SHIFT    8.0
                          HOURLY RATE  $ 6.00               210240.

        MAINTENANCE LABOR                                    25037.

        SUPERVISION                                          35292.

    ADMINISTRATION + OVERHEAD                               162341.

    SUPPLIES

        OPERATING                                            63072.

        MAINTENANCE                                          25037.

    LOCAL TAXES + INSURANCE                                  45066.
                                                --------------------
GROSS ANNUAL OPERATING COST                                 770602.

    CREDITS/PENALTIES COST                                       0.
                                                --------------------
NET ANNUAL OPERATING COST                                   770602.



              DISCOUNTED CASH FLOW METHOD
   RETURN ON            UNIT GAS COST
   INVESTMENT            ($/MM BTU)

      .10                   4.28
      .15                   5.53
      .20                   6.50
```

Table 6.13a

```
                        SYSTEM PERFORMANCE

FEED COMPOSITION

      TOTAL SOLIDS                                2000.0 TONS/D
      SOLIDS FRACTION IN FEED                       .500
      VOLATILE SOLIDS FRACTION IN SOLIDS            .950
      BIODEGR. VOL. SOL. FRACT. IN VOL SOL          .360



STORAGE
      NUMBER OF UNITS                             54.
      CAPACITY PER UNIT                        296296. CU.FT.

SHREDDING
      NUMBER OF UNITS                              7.
      CAPACITY PER UNIT                      .2381E+02 TONS/HR
      POWER REQUIREMENT                         .2500E+04 HP

HOLDING-MIXING

      NUMBER OF UNITS                              3.
      CAPACITY PER UNIT                      .2083E+06 CU FT.
      POWER REQUIREMENT                         .1250E+03 HP

PRETREATMENT-NONE USED

DIGESTION

   CSTR
      NUMBER OF UNITS                            69.
      CAPACITY PER UNIT                      .9964E+05 CU.FT.
      DIGESTER TEMPERATURE                       60.0
      RETENTION TIME                             10.0DAYS
      CONVERSION EFFICIENCY                       .767
      POWER REQUIREMENT                           .1375E+04HP

   GAS PRODUCTION                                 1.158 VVD
                                            .7961E+04 MM BTU/D
   HEAT EXCHANGER
      NUMBER OF UNITS                            21.
      HEAT EXCHANGER AREA                    .9533E+04 SQ.FT.

   TOTAL HEAT REQUIREMENT                    .7392E+03 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.13b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	515741.
SHREDDERS	374715.
HOLDING TANKS	634701.
DIGESTERS	9802033.
HEAT EXCHANGERS	1134220.
MATERIALS HANDLING EQUIPMENT	623071.
SUBTOTAL	13084481.
STRUCTURES-ELECT. + PIPING	523379.
SUBTOTAL	13607861.
SUPPORT FACILITIES	680393.
SUBTOTAL CAPITAL INVESTMENT	14288254.
CONTRACTOR OVERHEAD + PROFIT	142883.
ENGINEERING + DESIGN	714413.
SUBTOTAL PLANT INVESTMENT	15145549.
PROJECT CONTINGENCY	2271832.
TOTAL PLANT INVESTMENT	17417381.
INTEREST DURING CONSTRUCTION	1567564.
START-UP COSTS	961070.
WORKING CAPITAL	348348.
TOTAL CAPITAL REQUIREMENT	20294363.

Table 6.13c

```
                    ANNUAL OPERATING COSTS

                                                ANNUAL COST ($)


    PRODUCTION MATERIALS

         FEED - $    0.00/TON                                   0.

    UTILITIES

         ELECTRIC - 5.0 CTS./KW-HR                        1175523.

         FUEL   -   $ 5.00/MM BTU                          1517748.

    LABOR

         OPERATING LABOR - MEN PER DAY     24.
                           HRS PER SHIFT    8.0
                           HOURLY RATE   $ 6.00            420480.

         MAINTENANCE LABOR                                  261261.

         SUPERVISION                                        102261.

    ADMINISTRATION + OVERHEAD                               470401.

    SUPPLIES

         OPERATING                                          126144.

         MAINTENANCE                                        261261.

    LOCAL TAXES + INSURANCE                                 470269.
                                                   ------------------
 GROSS ANNUAL OPERATING COST                               4805348.

    CREDITS/PENALTIES COST                                       0.
                                                   ------------------
 NET ANNUAL OPERATING COST                                 4805348.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XX                                                                  XX
XX          TOTAL ANNUAL CAPITAL REQUIREMENT = $    7321079.        XX
XX                                                                  XX
XX          TOTAL ANNUAL GAS PRODUCTION =   2615117. MM BTU         XX
XX                                                                  XX
XX          UNIT GAS COST = $   2.80/MM BTU                         XX
XX                                                                  XX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


                 DISCOUNTED CASH FLOW METHOD
    RETURN ON              UNIT GAS COST
    INVESTMENT              ($/MM BTU)

        .10                   3.17
        .15                   4.45
        .20                   5.44
```

Table 6.14a

```
                         SYSTEM PERFORMANCE

FEED COMPOSITION

          TOTAL SOLIDS                                 2500.0 TONS/D
          SOLIDS FRACTION IN FEED                        .925
          VOLATILE SOLIDS FRACTION IN SOLIDS             .833
          BIODEGR. VOL. SOL. FRACT. IN VOL SOL           .500




STORAGE
          NUMBER OF UNITS                              67.
          CAPACITY PER UNIT                        298507. CU.FT.

SHREDDING
          NUMBER OF UNITS                                5.
          CAPACITY PER UNIT                      .2252E+02 TONS/HR
          POWER REQUIREMENT                              .1689E+04 HP

HOLDING-MIXING

          NUMBER OF UNITS                                3.
          CAPACITY PER UNIT                      .2604E+06 CU FT.
          POWER REQUIREMENT                              .1563E+03 HP

PRETREATMENT-NONE USED

DIGESTION

     CSTR
          NUMBER OF UNITS                              86.
          CAPACITY PER UNIT                      .9993E+05 CU.FT.
          DIGESTER TEMPERATURE                         60.0
          RETENTION TIME                               10.0DAYS
          CONVERSION EFFICIENCY                          .767
          POWER REQUIREMENT                              .1719E+04HP

     GAS PRODUCTION                                     1.375 VVD
                                                   .1181E+05 MM BTU/D
     HEAT EXCHANGER
          NUMBER OF UNITS                              25.
          HEAT EXCHANGER AREA                    .9953E+04 SQ.FT.

     TOTAL HEAT REQUIREMENT                      .8358E+03 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.14b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	642475.
SHREDDERS	257872.
HOLDING TANKS	715980.
DIGESTERS	12236192.
HEAT EXCHANGERS	1394639.
MATERIALS HANDLING EQUIPMENT	762358.
SUBTOTAL	16009516.
STRUCTURES-ELECT. + PIPING	640381.
SUBTOTAL	16649897.
SUPPORT FACILITIES	832495.
SUBTOTAL CAPITAL INVESTMENT	17482392.
CONTRACTOR OVERHEAD + PROFIT	174824.
ENGINEERING + DESIGN	874120.
SUBTOTAL PLANT INVESTMENT	18531335.
PROJECT CONTINGENCY	2779700.
TOTAL PLANT INVESTMENT	21311035.
INTEREST DURING CONSTRUCTION	1917993.
START-UP COSTS	1029325.
WORKING CAPITAL	426221.
TOTAL CAPITAL REQUIREMENT	24684574.

Table 6.14c

```
                           ANNUAL OPERATING COSTS

                                                         ANNUAL COST ($)


    PRODUCTION MATERIALS

        FEED - $    0.00/TON                                              0.

    UTILITIES

        ELECTRIC - 5.0 CTS./KW-HR                                   1047447.

        FUEL   -  $ 5.00/MM BTU                                     1716102.

    LABOR

        OPERATING LABOR - MEN PER DAY     24.
                          HRS PER SHIFT    8.0
                          HOURLY RATE    $ 6.00                      420480.

        MAINTENANCE LABOR                                            319666.

        SUPERVISION                                                  111022.

    ADMINISTRATION + OVERHEAD                                        510700.

    SUPPLIES

        OPERATING                                                    126144.

        MAINTENANCE                                                  319666.

    LOCAL TAXES + INSURANCE                                          575398.
                                                         --------------------
 GROSS ANNUAL OPERATING COST                                        5146624.

    CREDITS/PENALTIES COST                                                0.
                                                         --------------------
 NET ANNUAL OPERATING COST                                          5146624.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XX                                                    XX
XX        TOTAL ANNUAL CAPITAL REQUIREMENT = $    8206634.    XX
XX                                                    XX
XX        TOTAL ANNUAL GAS PRODUCTION =    3880766. MM BTU    XX
XX                                                    XX
XX        UNIT GAS COST = $   2.11/MM BTU                 XX
XX                                                    XX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


              DISCOUNTED CASH FLOW METHOD
   RETURN ON             UNIT GAS COST
   INVESTMENT             ($/MM BTU)

       .10                    2.42
       .15                    3.47
       .20                    4.29
```

Table 6.15a

```
                    SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                                 1750.0 TONS/D
        SOLIDS FRACTION IN FEED                        .900
        VOLATILE SOLIDS FRACTION IN SOLIDS             .940
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL           .420




STORAGE
        NUMBER OF UNITS                              47.
        CAPACITY PER UNIT                        297872. CU.FT.

SHREDDING
        NUMBER OF UNITS                                4.
        CAPACITY PER UNIT                      .2025E+02 TONS/HR
        POWER REQUIREMENT                          .1215E+04 HP

HOLDING-MIXING

        NUMBER OF UNITS                                2.
        CAPACITY PER UNIT                      .2734E+06 CU FT.
        POWER REQUIREMENT                          .1094E+03 HP

PRETREATMENT-NONE USED

DIGESTION

    CSTR
        NUMBER OF UNITS                              61.
        CAPACITY PER UNIT                      .9862E+05 CU.FT.
        DIGESTER TEMPERATURE                         60.C
        RETENTION TIME                               10.0DAYS
        CONVERSION EFFICIENCY                         .767
        POWER REQUIREMENT                             .1203E+04HP

    GAS PRODUCTION                                  1.315 VVD
                                               .7909E+04 MM BTU/D
    HEAT EXCHANGER
        NUMBER OF UNITS                              18.
        HEAT EXCHANGER AREA                    .9692E+04 SQ.FT.

    TOTAL HEAT REQUIREMENT                     .6048E+03 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 6.15b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	450174.
SHREDDERS	192137.
HOLDING TANKS	490063.
DIGESTERS	8617508.
HEAT EXCHANGERS	984308.
MATERIALS HANDLING EQUIPMENT	536709.
SUBTOTAL	11270898.
STRUCTURES-ELECT. + PIPING	450836.
SUBTOTAL	11721734.
SUPPORT FACILITIES	586087.
SUBTOTAL CAPITAL INVESTMENT	12307821.
CONTRACTOR OVERHEAD + PROFIT	123078.
ENGINEERING + DESIGN	615391.
SUBTOTAL PLANT INVESTMENT	13046290.
PROJECT CONTINGENCY	1956944.
TOTAL PLANT INVESTMENT	15003234.
INTEREST DURING CONSTRUCTION	1350291.
START-UP COSTS	785718.
WORKING CAPITAL	300065.
TOTAL CAPITAL REQUIREMENT	17439308.

Table 6.15c

```
                         ANNUAL OPERATING COSTS

                                                    ANNUAL COST ($)


     PRODUCTION MATERIALS

          FEED - $   0.00/TON                                      0.

     UTILITIES

          ELECTRIC - 5.0 CTS./KW-HR                           742865.

          FUEL   -   $ 5.00/MM BTU                           1241674.

     LABOR

          OPERATING LABOR - MEN PER DAY     24.
                            HRS PER SHIFT   8.0
                            HOURLY RATE   $ 6.00              420480.

          MAINTENANCE LABOR                                   225049.

          SUPERVISION                                          96829.

     ADMINISTRATION + OVERHEAD                                445415.

     SUPPLIES

          OPERATING                                           126144.

          MAINTENANCE                                         225049.

     LOCAL TAXES + INSURANCE                                  405087.
                                                    -------------------
 GROSS ANNUAL OPERATING COST                                 3928591.

     CREDITS/PENALTIES COST                                        0.
                                                    -------------------
 NET ANNUAL OPERATING COST                                   3928591.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XX                                                                XX
XX         TOTAL ANNUAL CAPITAL REQUIREMENT = $    6090421.        XX
XX                                                                XX
XX         TOTAL ANNUAL GAS PRODUCTION =   2598018. MM BTU         XX
XX                                                                XX
XX         UNIT GAS COST = $   2.34/MM BTU                         XX
XX                                                                XX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


                  DISCOUNTED CASH FLOW METHOD
        RETURN ON          UNIT GAS COST
        INVESTMENT          ($/MM BTU)


           .10               2.67
           .15               3.77
```

biodegradable volatile solids of 77%. The fractional conversion of volatile solids is dependent on the fractional content of biodegradable solids in the feed; the conversions are 28, 38, and 32% for corn stover, rice straw, and wheat straw, respectively. The small scale system utilizes a CSTR at a lower temperature, 35°C, and longer retention time, 16 days. This leads to a lower fractional conversion of biodegradable volatile solids, 45%, and a lower conversion of volatile solids; 16, 23, and 19% for corn stover, rice straw, and wheat straw, respectively. If the small scale case were to utilize 60°C and 10 day retention time operation, the unit gas costs would be about 40% lower than presented in Figures 6.1 - 6.3.

In all cases, the unit gas costs are highest for corn stover and lowest for rice straw. One reason for this is the gas production for rice straw is about 50% greater than for corn stover or wheat straw. This higher output is due to high residue content per acre and high biodegradable solids content in the residue. The corn stover and wheat straw produce approximately the same amount of gas, but the corn stover utilizes more residue due to a higher per acre residue yield. This increased amount of residue requires larger equipment sizes and correspondingly larger power and heat requirements, thus resulting in a greater unit gas cost for corn stover compared to wheat straw.

Another interesting comparison is the relative contributions due to fixed and operating costs. For the small-, medium-, and large-scale systems the ratio of operating to fixed costs are approximately 0.5, 2.2, and 1.4, respectively. The small scale system has a low ratio since all labor and supplies costs were assumed to be zero. For the medium and large scale systems, labor and supplies costs accounted for approximately 60 and 35% of operating costs, respectively, which results in the high ratios of operating costs to fixed costs.

The major contribution to capital costs is due to digester cost, which accounts for approximately 70, 70, and 75% of capital costs for small-, medium-, and large-scale systems, respectively. Approaches which lead to lower digester capital costs should result in significant reductions in unit gas costs.

The energy balance for a conversion process is an important consideration in design. Obviously, a system must utilize less energy than it produces. For the small scale size system with corn stover feedstock (the lowest energy output), the system utilizes about 50% of the energy it produces. The energy balance is slightly better for rice straw and wheat straw. For the medium and large scale systems with corn stover, the process utilizes 25% of the energy it produces, which is better then the small scale system. Since the medium and large scale systems operate at thermophilic conditions, the conversion and gas production are greater than for the small scale system, thus giving a more favorable energy balance.

The results of the base line systems analysis indicate which factors make large contributions to unit gas costs. Approaches to abate these costs by appropriately altering these factors are discussed in the sensitivity analysis in Section 7.

Section 7

SENSITIVITY ANALYSIS

The results presented in Section 6 were for specified base line conditions. These conditions were established from prior experience with similar processes. In this section, the effects of varying some of these base line parameters on system economics is presented.

7.1 Digestion

The digestion conditions assumed for the base line systems are presented in Table 6. One significant change from these conditions is to utilize a batch digestion process. A second variation is CSTR retention time.

7.1.1. Batch Digestion

A controlled landfill concept is incorporated with a low capital cost reactor (e.g., a hole-in-the-ground concept as the batch digester). For the batch landfill system, the digestion temperature is assumed to be 35°C. For this temperature, the reaction rate constant utilized is one which would yield 60% conversion of biodegradables in 6 months, as was obtained in laboratory experiments (Refs. 114, 133). Buffer chemical addition is included for the batch process, equal to 1% of the solids content, and at a cost of $30/ton. The results are presented in Figures 7.1, 7.2, and 7.3 for batch digestion of corn stover, rice straw, and wheat straw, respectively, over a range of batch digestion retention times. (The costs in these figures and all other figures are for 10% ROI DCF unless otherwise indicated). Details of the analysis are presented in Tables 7.1, 7.2, and 7.3 for small-, medium-, and large-scale batch digestion of corn stover (at a 180 day retention time).

Analysis of the results indicates that for the range of batch digestion retention times of 6 months to 1 year , the gas cost is lower for the higher retention times. This is due to the large difference in conversion efficiencies (e.g., 60% at 6 months and 83% for 1 year) and the corresponding

Figure 7.1

UNIT GAS COST FOR BATCH DIGESTION OF CORN STOVER

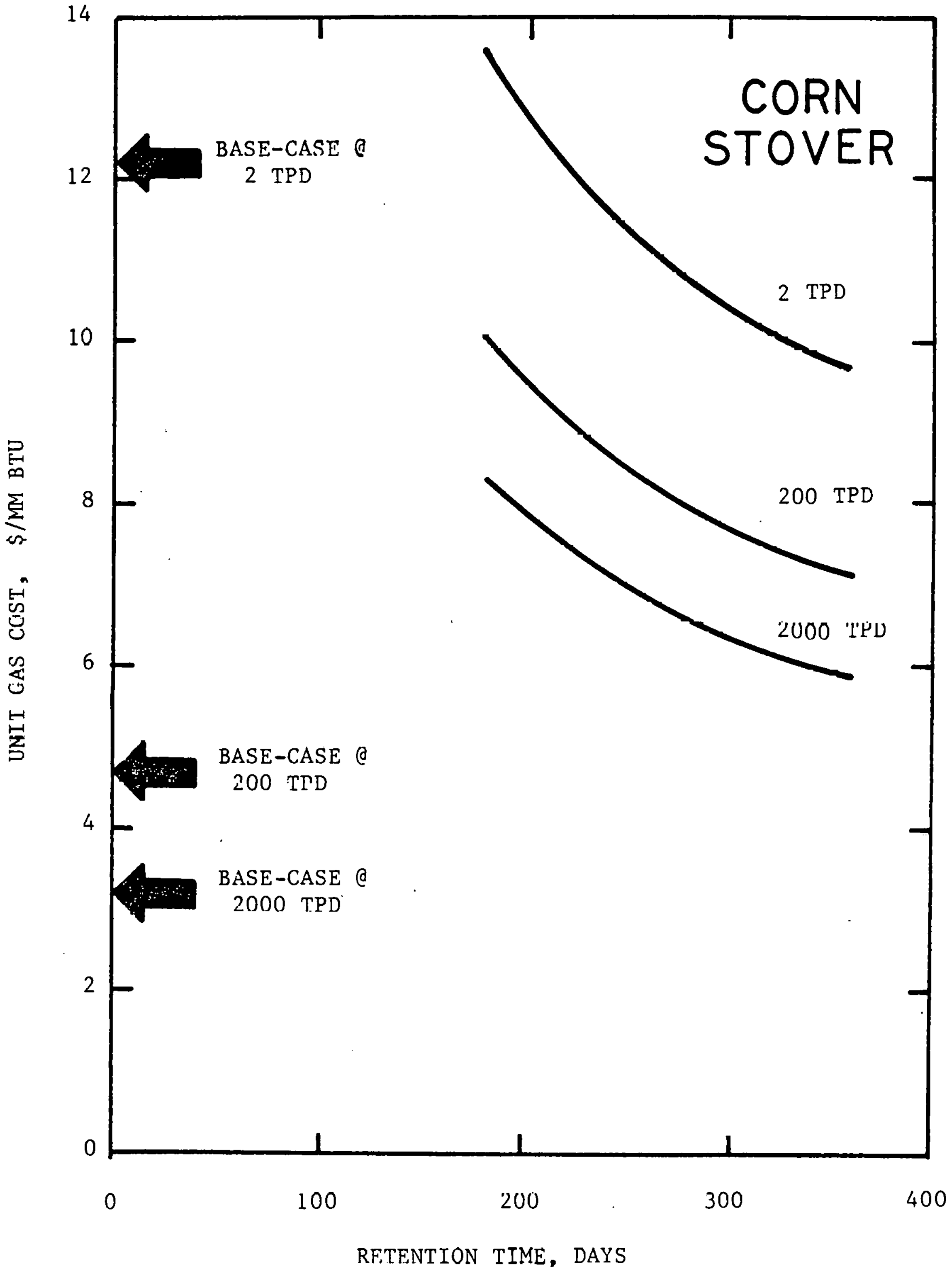


Figure 7.2

UNIT GAS COST FOR BATCH DIGESTION OF RICE STRAW

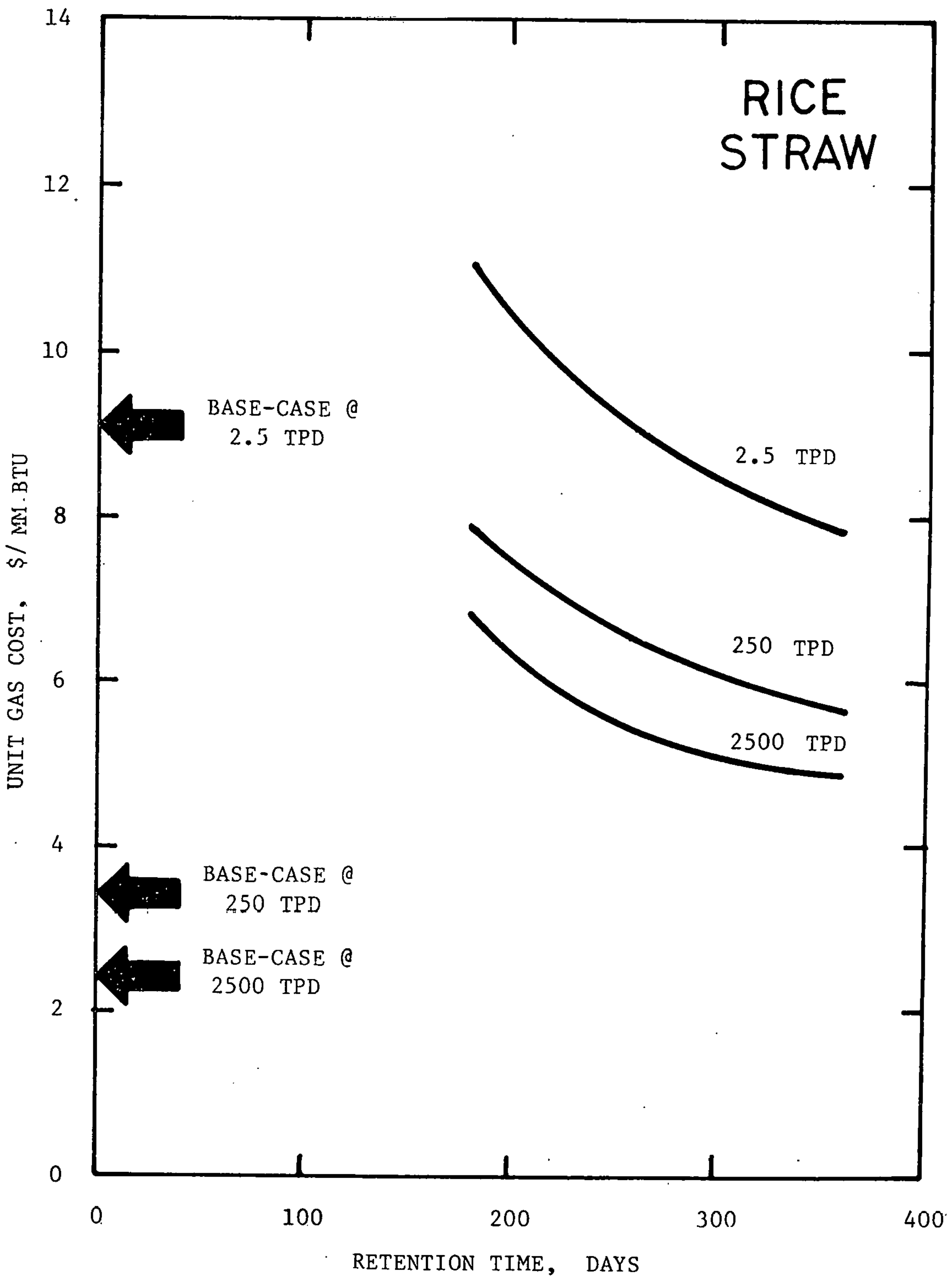


Figure 7.3

UNIT GAS COST FOR BATCH DIGESTION OF WHEAT STRAW

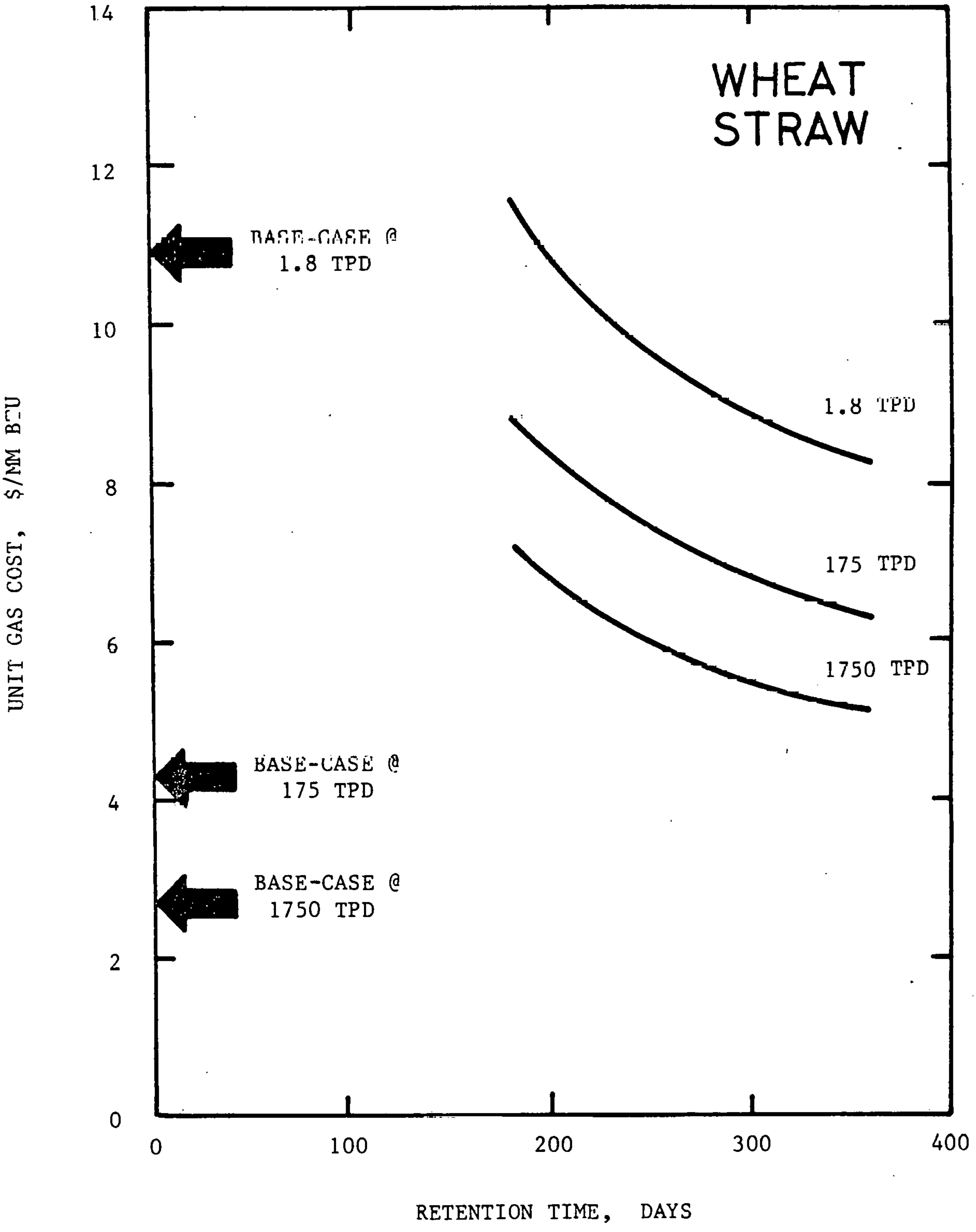


Table 7.1

SYSTEM DESIGN FOR BATCH DIGESTION OF CORN STOVER - SMALL SCALE

Table 7.1a

```
                                   SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                                      2.0  TONS/D
        SOLIDS FRACTION IN FEED                          .500
        VOLATILE SOLIDS FRACTION IN SOLIDS               .950
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL             .360



STORAGE - NONE USED

SHREDDING
        NUMBER OF UNITS                                1.
        CAPACITY PER UNIT                       .2028E+01 TONS/HR
        POWER REQUIREMENT                                .3042E+02 HP

HOLDING-NONE USED

PRETREATMENT-NONE USED

DIGESTION

    BATCH
        NUMBER OF UNITS                                1.
        CAPACITY PER UNIT                       .2509E+06 CU.FT.
        DIGESTER TEMPERATURE                          35.0
        RETENTION TIME                               180.0DAYS
        CONVERSION EFFICIENCY                           .591
        POWER REQUIREMENT                               0.          HP

    GAS PRODUCTION                                      .050 VVD
                                                   .1243E+02 MM BTU/D

    TOTAL HEAT REQUIREMENT                   0.             MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 7.1b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
SHREDDERS	10277.
DIGESTERS	107449.
MATERIALS HANDLING EQUIPMENT	5886.
SUBTOTAL	123613.
STRUCTURES-ELECT. + PIPING	4945.
SUBTOTAL	128558.
SUPPORT FACILITIES	6428.
SUBTOTAL CAPITAL INVESTMENT	134986.
CONTRACTOR OVERHEAD + PROFIT	1350.
ENGINEERING + DESIGN	6749.
SUBTOTAL PLANT INVESTMENT	143085.
PROJECT CONTINGENCY	21463.
TOTAL PLANT INVESTMENT	164547.
INTEREST DURING CONSTRUCTION	14809.
START-UP COSTS	1100.
WORKING CAPITAL	3291.
TOTAL CAPITAL REQUIREMENT	183748.

Table 7.1c

```
                         ANNUAL OPERATING COSTS

                                                      ANNUAL COST ($)

     PRODUCTION MATERIALS

          FEED - $   0.00/TON                                       0.

          BUFFER CHEMICAL                                         241.

     UTILITIES

          ELECTRIC - 5.0 CTS./KW-HR                               816.

          FUEL   -   $ 5.00/MM BTU                                  0.

     LABOR

          OPERATING LABOR - MEN PER DAY      1.
                            HRS PER SHIFT   8.0
                            HOURLY RATE   $ 0.00                    0.

          MAINTENANCE LABOR                                         0.

          SUPERVISION                                               0.

     ADMINISTRATION + OVERHEAD                                      0.

     SUPPLIES

          OPERATING                                                 0.

          MAINTENANCE                                               0.

     LOCAL TAXES + INSURANCE                                     4443.
                                                     --------------------
  GROSS ANNUAL OPERATING COST                                    5500.

     CREDITS/PENALTIES COST                                         0.
                                                     --------------------
  NET ANNUAL OPERATING COST                                      5500.


              DISCOUNTED CASH FLOW METHOD
    RETURN ON           UNIT GAS COST
    INVESTMENT           ($/MM BTU)

       .10                 13.67
       .15                 20.85
       .20                 27.87
```

Table 7.2

SYSTEM DESIGN FOR BATCH DIGESTION OF CORN STOVER - MEDIUM SCALE

Table 7.2a

```
                              SYSTEM PERFORMANCE

FEED COMPOSITION

          TOTAL SOLIDS                                      200.0 TONS/D
          SOLIDS FRACTION IN FEED                            .500
          VOLATILE SOLIDS FRACTION IN SOLIDS                 .950
          BIODEGR. VOL. SOL. FRACT. IN VOL SOL               .360



STORAGE - NONE USED

SHREDDING
          NUMBER OF UNITS                                      3.
          CAPACITY PER UNIT                          .2253E+02 TONS/HR
          POWER REQUIREMENT                                  .1014E+04 HP

HOLDING-NONE USED

PRETREATMENT-NONE USED

DIGESTION

     BATCH
          NUMBER OF UNITS                                    26.
          CAPACITY PER UNIT                          .9651E+06 CU.FT.
          DIGESTER TEMPERATURE                               35.0
          RETENTION TIME                                   180.0DAYS
          CONVERSION EFFICIENCY                               .591
          POWER REQUIREMENT                                   0.        HP

     GAS PRODUCTION                                           .050 VVD
                                                        .1243E+04 MM BTU/D

     TOTAL HEAT REQUIREMENT                          0.            MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 7.2b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
SHREDDERS	154761.
DIGESTERS	4356059.
MATERIALS HANDLING EQUIPMENT	225541.
SUBTOTAL	4736361.
STRUCTURES-ELECT. + PIPING	189454.
SUBTOTAL	4925815.
SUPPORT FACILITIES	246291.
SUBTOTAL CAPITAL INVESTMENT	5172106.
CONTRACTOR OVERHEAD + PROFIT	51721.
ENGINEERING + DESIGN	258605.
SUBTOTAL PLANT INVESTMENT	5482432.
PROJECT CONTINGENCY	822365.
TOTAL PLANT INVESTMENT	6304797.
INTEREST DURING CONSTRUCTION	567432.
START-UP COSTS	198890.
WORKING CAPITAL	126096.
TOTAL CAPITAL REQUIREMENT	7197215.

Table 7.2c

```
                    ANNUAL OPERATING COSTS

                                                   ANNUAL COST ($)


  PRODUCTION MATERIALS

       FEED - $    0.00/TON                                       0.

       BUFFER CHEMICAL                                        24090.

  UTILITIES

       ELECTRIC - 5.0 CTS./KW-HR                              81634.

       FUEL   -   $ 5.00/MM BTU                                   0.

  LABOR

       OPERATING LABOR - MEN PER DAY     12.
                         HRS PER SHIFT    8.0
                         HOURLY RATE   $ 6.00                210240.

       MAINTENANCE LABOR                                      94572.

       SUPERVISION                                            45722.

  ADMINISTRATION + OVERHEAD                                  210320.

  SUPPLIES

       OPERATING                                              63072.

       MAINTENANCE                                            94572.

  LOCAL TAXES + INSURANCE                                    170230.
                                               --------------------
GROSS ANNUAL OPERATING COST                                  994451.

  CREDITS/PENALTIES COST                                          0.
                                               --------------------
NET ANNUAL OPERATING COST                                    994451.



            DISCOUNTED CASH FLOW METHOD
  RETURN ON            UNIT GAS COST
  INVESTMENT            ($/MM BTU)

     .10                  10.02
     .15                  15.39
     .20                  19.56
```

Table 7.3

SYSTEM DESIGN FOR BATCH DIGESTION OF CORN STOVER - LARGE SCALE

Table 7.3a

```
                         SYSTEM PERFORMANCE

FEED COMPOSITION

          TOTAL SOLIDS                                2000.0 TONS/D
          SOLIDS FRACTION IN FEED                       .500
          VOLATILE SOLIDS FRACTION IN SOLIDS            .950
          BIODEGR. VOL. SOL. FRACT. IN VOL SOL          .360



STORAGE - NONE USED

SHREDDING
          NUMBER OF UNITS                            28.
          CAPACITY PER UNIT                       .2414E+02 TONS/HR
          POWER REQUIREMENT                             .1014E+05 HP

HOLDING-NONE USED

PRETREATMENT-NONE USED

DIGESTION

     BATCH
          NUMBER OF UNITS                           251.
          CAPACITY PER UNIT                       .9998E+06 CU.FT.
          DIGESTER TEMPERATURE                        35.0
          RETENTION TIME                            180.0DAYS
          CONVERSION EFFICIENCY                         .591
          POWER REQUIREMENT                            0.           HP

     GAS PRODUCTION                                     .350 VVD
                                                   .1243E+05 MM BTU/D

     TOTAL HEAT REQUIREMENT                0.              MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 7.3b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
SHREDDERS	1512776.
DIGESTERS	43560586.
MATERIALS HANDLING EQUIPMENT	2253668.
SUBTOTAL	47327030.
STRUCTURES-ELECT. + PIPING	1893081.
SUBTOTAL	49220111.
SUPPORT FACILITIES	2461006.
SUBTOTAL CAPITAL INVESTMENT	51681117.
CONTRACTOR OVERHEAD + PROFIT	516811.
ENGINEERING + DESIGN	2584056.
SUBTOTAL PLANT INVESTMENT	54781984.
PROJECT CONTINGENCY	8217298.
TOTAL PLANT INVESTMENT	62999281.
INTEREST DURING CONSTRUCTION	5669935.
START-UP COSTS	1268363.
WORKING CAPITAL	1259986.
TOTAL CAPITAL REQUIREMENT	71197565.

Table 7.3c

```
                         ANNUAL OPERATING COSTS

                                                      ANNUAL COST ($)

    PRODUCTION MATERIALS

        FEED - $   0.00/TON                                          0.

        BUFFER CHEMICAL                                         240900.

    UTILITIES

        ELECTRIC - 5.0 CTS./KW-HR                               816336.

        FUEL   -   $ 5.00/MM BTU                                     0.

    LABOR

        OPERATING LABOR - MEN PER DAY     24.
                          HRS PER SHIFT    8.0
                          HOURLY RATE    $ 6.00                 420480.

        MAINTENANCE LABOR                                       944989.

        SUPERVISION                                             204820.

    ADMINISTRATION + OVERHEAD                                   942174.

    SUPPLIES

        OPERATING                                               126144.

        MAINTENANCE                                             944989.

    LOCAL TAXES + INSURANCE                                    1700981.
                                                  --------------------
 GROSS ANNUAL OPERATING COST                                   6341813.

    CREDITS/PENALTIES COST                                           0.
                                                  --------------------
 NET ANNUAL OPERATING COST                                     6341813.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XX                                                                   XX
XX         TOTAL ANNUAL CAPITAL REQUIREMENT = $    15168502.        XX
XX                                                                   XX
XX         TOTAL ANNUAL GAS PRODUCTION =    2236548. MM BTU         XX
XX                                                                   XX
XX         UNIT GAS COST = $    6.78/MM BTU                         XX
XX                                                                   XX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

              DISCOUNTED CASH FLOW METHOD
   RETURN ON            UNIT GAS COST
   INVESTMENT            ($/MM BTU)

      .10                   8.36
      .15                  13.72
      .20                  17.86
```

difference in gas production.

A comparison of batch digestion with the base case CSTR system indicates several interesting results. For the medium and large sizes, the base case CSTR system results in a lower unit gas cost than the batch process. For the small scale system, the batch process is equivalent to or better than the CSTR. There are several reasons for this. First is the gas production. For the base line CSTR design, the medium and large scale systems utilize 60°C, whereas for the small scale, a 35°C digestion temperature is incorporated. The conversion efficiency is much higher for the thermophilic mode than for mesophilic, whether a batch or CSTR digestion is employed. Thus, the gas production for the medium and large scale systems is about 15% greater than the batch process (at 180 days retention time). For the small scale system, the gas production is 50% greater for the batch system (at 180 days retention time). These differences in gas production are partial contributors to the variations in unit gas cost.

A second cause of the differences in unit gas costs is due to the capital cost of the digester. The batch system utilizes a low cost per unit volume reactor, but because all the solids must be loaded in the reactor initially, the volume of the reactor for batch operation is significantly greater than for the CSTR mode, 20 and 35 times greater for the small and large scales, respectively. The density and concentration of solids also affects the size and cost of the digester. Typically, a density of 40 lb/ft^3 is maximum for a landfill, compared to about 64 lb/ft^3 for a continuous flow system. The solids content for the landfill is about 20% whereas it is 10% for the continuous process. The digester cost for the large scale batch system (for corn stover) is $44 million, which is 4.5 times the $9.8 million for the base line CSTR design for corresponding conditions. This ratio is much lower than the ratio of digester volumes due to the lower per volume digester cost for the batch system, $\$4.70/yd^3$, compared to $\$40/yd^3$ for the CSTR digester. For the small scale system the batch digester cost is $100,000, which is 2.3 times the CSTR digester cost of $43,000.

It should be noted that the major cost item for the small scale batch system was for the digester. Since this is a hole-in-the-ground digester it is possible this cost could be reduced significantly by having the farmer construct the digester. If the digester cost were reduced by 50%, the unit gas cost would also decrease by about 50% since the digester cost contributes about 90% to the gas cost.

These results, which indicate the relative economic advantage of the small scale batch system over the conventional CSTR, indicate that development for small farm digestion of crop residues should continue on the controlled landfill concept. This system probably has the advantage of requiring less labor input, once the system is initiated, a desirable characteristic for small farm operation; i.e., there is no need for periodic loading of residue as is the case for a continuous digestion.

Since it is indicated that small scale batch digestion has a potential economic advantage over a continuous process, it is important to describe the scenario for this process. The crop residue is addded to the digester with the appropriate addition of manure (inoculum and nutrient), buffer, and water to provide a mixture which will result in a high rate of gas production. This loading and admixing step should take about one month. The digestion process will be designed to result in 60% conversion of biodegradable matter in six months. However, the digestion process could continue up to ten months, which would yield about 78% conversion after which time the digester is unloaded and prepared for the residue obtained from the next season's crop. This unloading step should take one month. The total cycle will thus be 12 months, with one month each for loading and unloading,and up to 10 months for digestion.

It should be noted that several critical factors could influence this scenario. First, it is necessary to start the batch digester at the appropriate time to ensure maximum gas production at the time of maximum need, i.e., the winter months. Also, it is essential that the periods of intensive labor input (loading and unloading) for this process do not coincide with other high labor farm operations (such as crop harvesting). To meet such conditions will probably require use of a residue system. The actual timing of this process will be dependent on location and crop residue utilized.

7.1.2 Digester Retention Time

The effect of varying CSTR digester retention time is shown in Figures 7.4, 7.5, and 7.6 for corn stover, rice straw, and wheat straw for the medium and large scale systems. The effect of decreasing retention time is to decrease the digester volume; therefore the capital cost is also decreased. However, lowering retention time decreases the fractional conversion and hence the gas production. The effects of these opposing factors results in decreasing gas cost with lowering of the retention time in the range of 4 to 16 days for the digestion conditions and feedstocks incorporated in this analysis. The decrease in unit gas cost is about 20% for the large scale system when going from 10 days to 6 days retention time. Pfeffer has found stable thermophilic digestion for retention times as low as four days for digestion of corn stover.

7.2 Pretreatment

The results for the base line systems designs show that the fractional conversion of volatile solids is extremely low, less than 40%; i.e., less than 40% of the heating value of biomass is obtained in the form of methane. One approach to improve the yield is to use a pretreatment step to solubilize the originally non-biodegradable volatile solids. Chemical and/or thermal processing can be used to improve the yield (Ref. 75, 112).

The effect of pretreatment added to all the base line cases was analyzed, and the results are presented in Table 7.4 for corn stover, rice straw, and wheat straw. Details of the analysis are presented in Table 7.5 for pretreatment/digestion of corn stover for 200 tons per day (tpd) throughput and 5% pretreatment chemical requirement. The conditions of pretreatment utilized in these analyses were 115°C temperature, 4 hours retention time, 50% conversion of non-biodegradable volatile solids to biodegradable volatile solids, and 5% loss of input biodegradable solids. The chemical pretreatment conversion of 50% was with addition of sodium hydroxide which has a cost of about $300/ton.

Figure 7.4

EFFECT OF CSTR RETENTION TIME ON
UNIT GAS COST FOR CORN STOVER

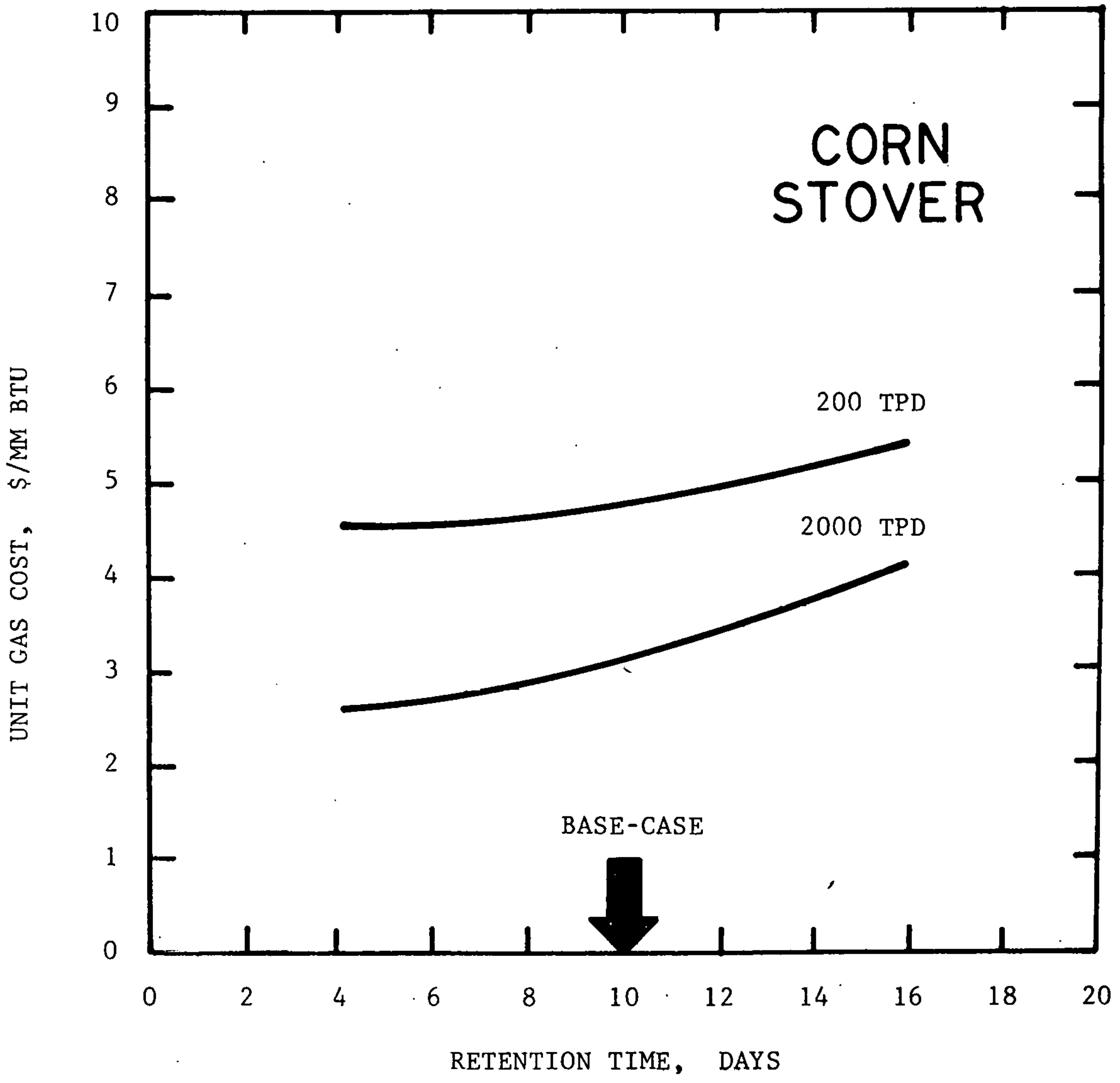


Figure 7.5

EFFECT OF CSTR RETENTION TIME ON
UNIT GAS COST FOR RICE STRAW

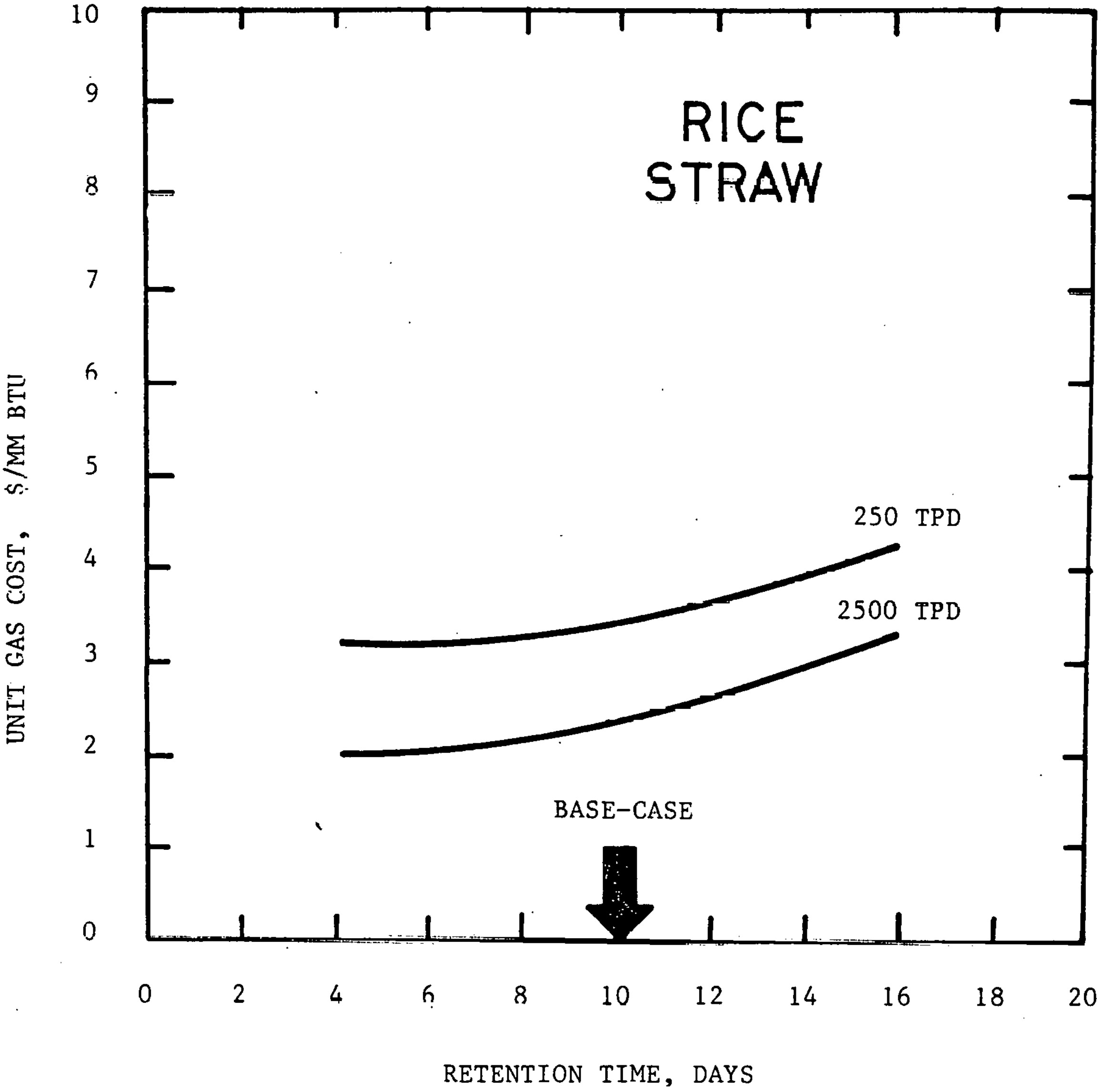


Figure 7.6

EFFECT OF CSTR RETENTION TIME ON
UNIT GAS COST FOR WHEAT STRAW

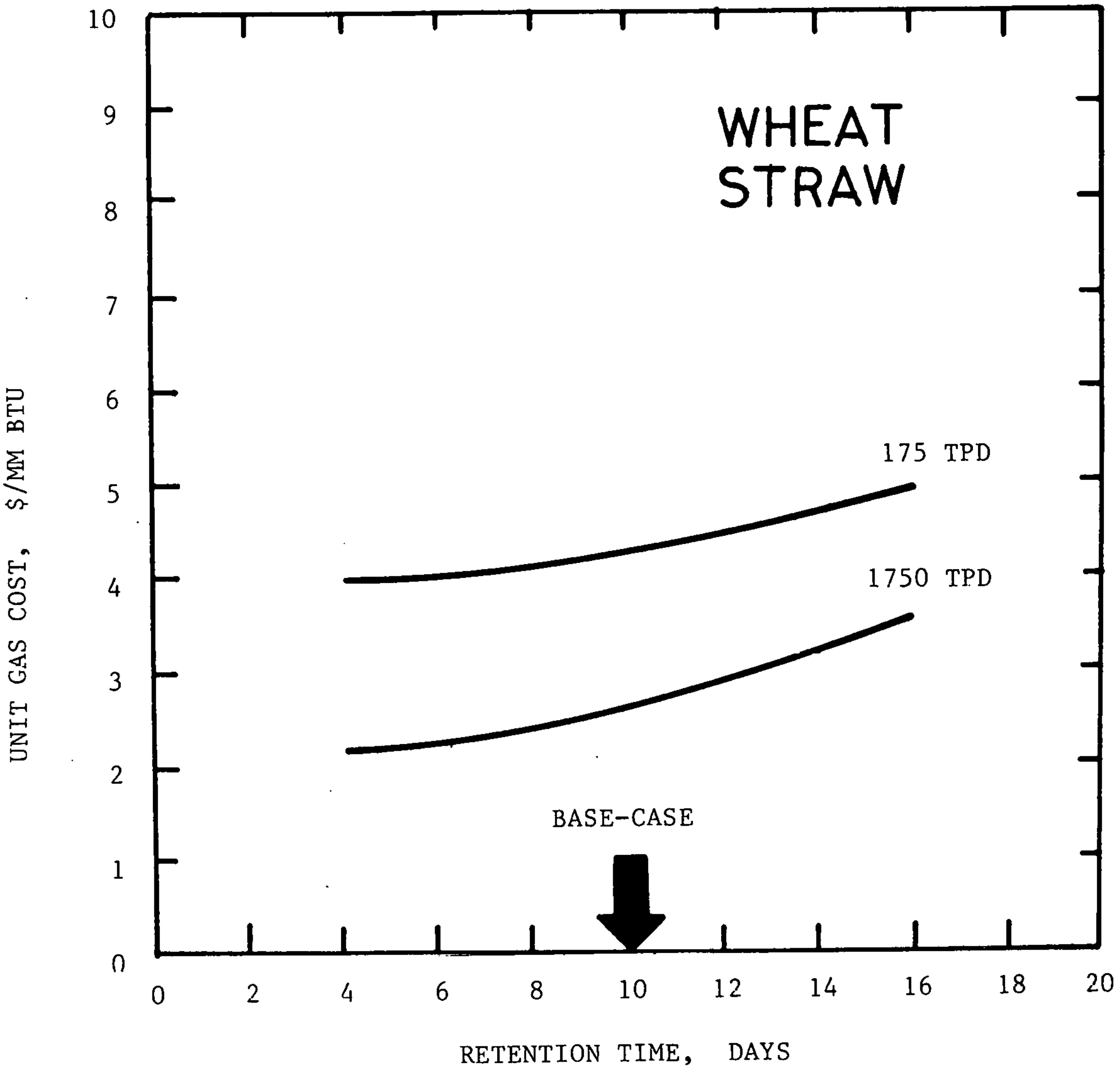


Table 7.4

Effect of Pretreatment* on Residue Digestion

	Corn Stover	Rice Straw	Wheat Straw
Small Scale			
Annual Gas Production (MM Btu)	2.68×10^3	3.2×10^3	2.4×10^3
Unit Gas Cost ($/MM Btu)	12.81	12.36	12.76
Intermediate Scale			
Annual Gas Production (MM Btu)	4.56×10^5	5.47×10^5	4.10×10^5
Unit Gas Cost ($/MM Btu)	5.29	5.18	5.15
Large Scale			
Annual Gas Production (MM Btu)	4.56×10^6	5.47×10^6	4.10×10^6
Unit Gas Cost ($/MM Btu)	4.33	4.38	4.15

* Pretreatment Conditions

NaOH Requirements = 5% of feed solids
Conversion = 50% of non-biodegradable solids
Temperature = 115°C
Retention Time = 4 Hours

Table 7.5

SYSTEM DESIGN FOR DIGESTION OF CORN STOVER UTILIZING PRETREATMENT MEDIUM SCALE

Table 7.5a

```
                         SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                                  200.0 TONS/D
        SOLIDS FRACTION IN FEED                        .500
        VOLATILE SOLIDS FRACTION IN SOLIDS             .950
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL           .360




STORAGE
        NUMBER OF UNITS                               6.
        CAPACITY PER UNIT                        266667. CU.FT.

SHREDDING
        NUMBER OF UNITS                               1.
        CAPACITY PER UNIT                      .1667E+02 TONS/HR
        POWER REQUIREMENT                              .2500E+03 HP

HOLDING-MIXING

        NUMBER OF UNITS                               1.
        CAPACITY PER UNIT                      .6250E+05 CU FT.
        POWER REQUIREMENT                              .1250E+02 HP

PRETREATMENT
        RATIO OF CHEMICAL TO FEED                      .050
        CONVERSION EFFICIENCY                          .500
        NUMBER OF UNITS                               2.
        CAPACITY PER UNIT                      .5469E+04 CU.FT.
        CHEMICAL REQUIREMENT                   .1000E+02 TONS/HR
        POWER REQUIREMENT                             0.          HP

DIGESTION

    CSTR
        NUMBER OF UNITS                               8.
        CAPACITY PER UNIT                      .9023E+05 CU.FT.
        DIGESTER TEMPERATURE                         60.C
        RETENTION TIME                               10.0DAYS
        CONVERSION EFFICIENCY                          .767
        POWER REQUIREMENT                              .1444E+03HP

    GAS PRODUCTION                                    1.921 VVD
                                                  .1387E+04 MM BTU/D
    HEAT EXCHANGER
        NUMBER OF UNITS                               3.
        HEAT EXCHANGER AREA                    .6857E+04 SQ.FT.

    TOTAL HEAT REQUIREMENT                     .9811E+02 MM BTU/D

DEWATERING-NONE USED

GAS PURIFICATION-NONE USED
```

Table 7.5b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	54135.
SHREDDERS	42152.
HOLDING TANKS	110432.
PRETREATMENT	236643.
DIGESTERS	1077232.
HEAT EXCHANGERS	126696.
MATERIALS HANDLING EQUIPMENT	82364.
SUBTOTAL	1729654.
STRUCTURES-ELECT. + PIPING	69186.
SUBTOTAL	1798841.
SUPPORT FACILITIES	89942.
SUBTOTAL CAPITAL INVESTMENT	1888783.
CONTRACTOR OVERHEAD + PROFIT	18888.
ENGINEERING + DESIGN	94439.
SUBTOTAL PLANT INVESTMENT	2002110.
PROJECT CONTINGENCY	300316.
TOTAL PLANT INVESTMENT	2302426.
INTEREST DURING CONSTRUCTION	207218.
START-UP COSTS	383331.
WORKING CAPITAL	46049.
TOTAL CAPITAL REQUIREMENT	2939024.

Table 7.5c

```
                     ANNUAL OPERATING COSTS
                                                  ANNUAL COST ($)


    PRODUCTION MATERIALS

         FEED - $    0.00/TON                                    0.

         PRETREATMENT CHEMICAL    $ 300.00/TON              985500.

    UTILITIES

         ELECTRIC - 5.0 CTS./KW-HR                          119573.

         FUEL   -   $ 5.00/MM BTU                           201422.

    LABOR

         OPERATING LABOR - MEN PER DAY     12.
                           HRS PER SHIFT    8.0
                           HOURLY RATE   $ 6.00             210240.

         MAINTENANCE LABOR                                   34536.

         SUPERVISION                                         36716.

    ADMINISTRATION + OVERHEAD                               168896.

    SUPPLIES

         OPERATING                                           63072.

         MAINTENANCE                                         34536.

    LOCAL TAXES + INSURANCE                                  62166.
                                                     --------------------
GROSS ANNUAL OPERATING COST                                1916657.

    CREDITS/PENALTIES COST                                       0.
                                                     --------------------
NET ANNUAL OPERATING COST                                  1916657.


                  DISCOUNTED CASH FLOW METHOD
   RETURN ON             UNIT GAS COST
   INVESTMENT             ($/MM BTU)

       .10                   5.29
       .15                   6.29
       .20                   7.07
```

Pfeffer and Quindry (Ref. 112) presented economics for pretreatment and digestion of corn stover. Pfeffer and Quindry obtained a unit gas cost of about \$10/MM Btu compared to about \$4.30/MM Btu for the analysis presented in this study. However, Pfeffer's economic analysis uses net energy production, whereas in this study the gross energy output is used. The net gas output used by Pfeffer of 143 GJ/hr is about half of the gross value calculated using the composition and conversion parameters in this report. This gross value would yield a gas cost of about \$5/MM Btu, which is comparable to the results presented for this study.

The results of the analysis of pretreatment indicates that the cost of chemical significantly affects the unit gas cost. For 5% chemical requirement, chemical cost is about 50% of operating cost for medium and large scale systems. This chemical cost is a critical factor in the unit gas cost resulting from pretreatment digestion of crop residue and suggests approaches in pretreatment processing to reduce unit gas cost. These alternative methods include use of lower cost chemicals or less chemical. However, experimental evidence results in less conversion to biodegradables (Ref. 112a) so that the gas production is less and unit gas cost is higher. For example, if use of 2.5% NaOH were to result in only 25% conversion of non-biodegradables, the unit gas cost for pretreatment/digestion of corn stover (for the intermediate size) will be approximately \$5.35/MM Btu. This compares to about \$5.29/MM Btu for the 5% NaOH pretreatment case, i.e., essentially no difference in unit gas cost.

The capital cost increase due to the pretreatment process is only about 15%. Thus, the use of pretreatment would be justified if good conversion can be obtained with either low chemical requirement or use of chemicals with lower cost. An analysis was made of varying pretreatment conditions from a chemical requirement of 0 to 30 percent of feedstock, assuming that 50% of the non-biodegradable volatile solids fraction is converted to biodegradable solids. The results of this analysis are presented in Figures 7.7, 7.8, and 7.9 for corn stover, rice straw, and wheat straw, respectively. It should be reemphasized that the available experimental data indicate that a reduction in chemical addition results in a lower fractional conversion to biodegradable solids.

Figure 7.7

EFFECT OF PRETREATMENT ON UNIT GAS COST
CORN STOVER

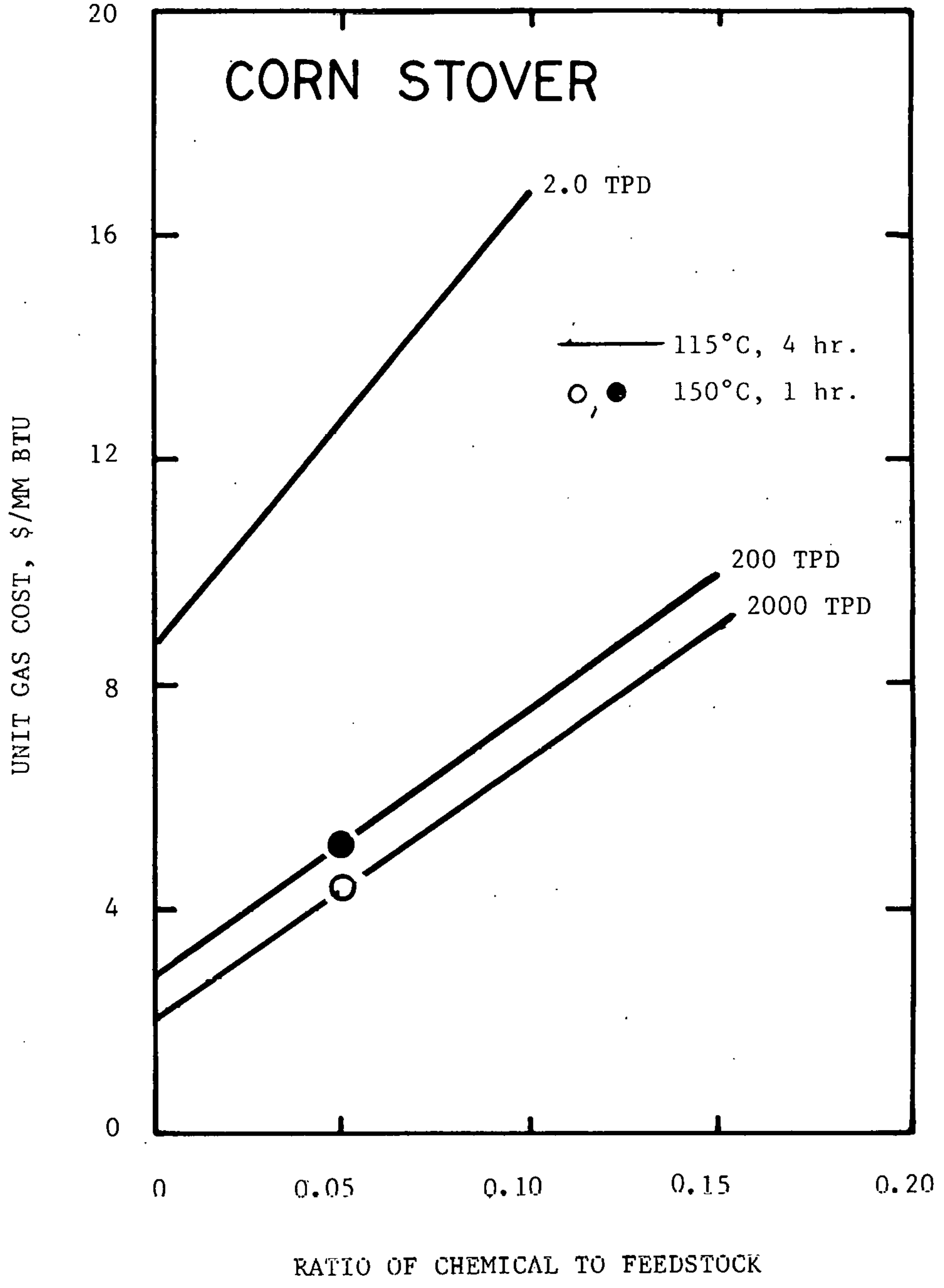


Figure 7.8

EFFECT OF PRETREATMENT ON UNIT GAS COST
RICE STRAW

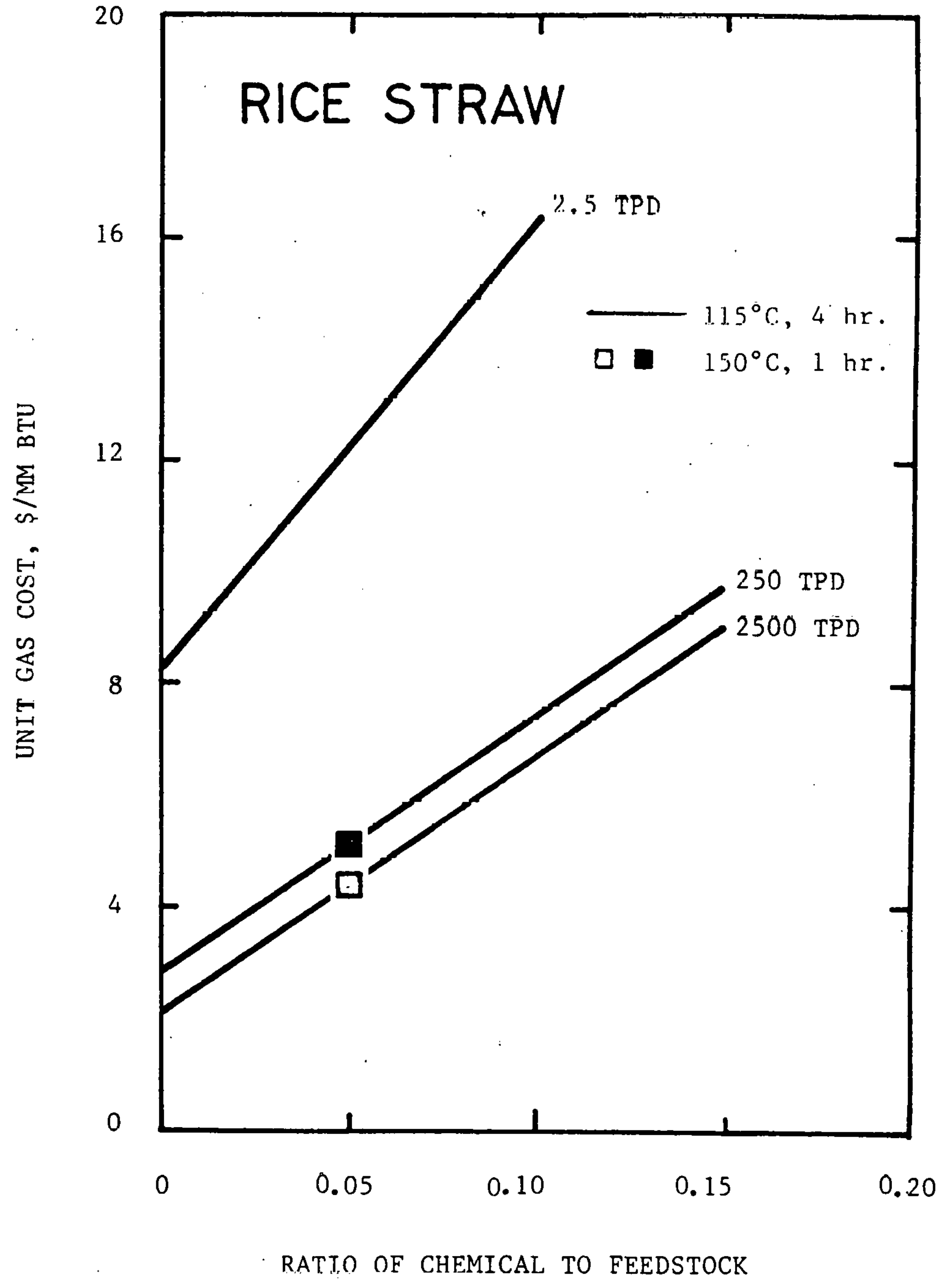
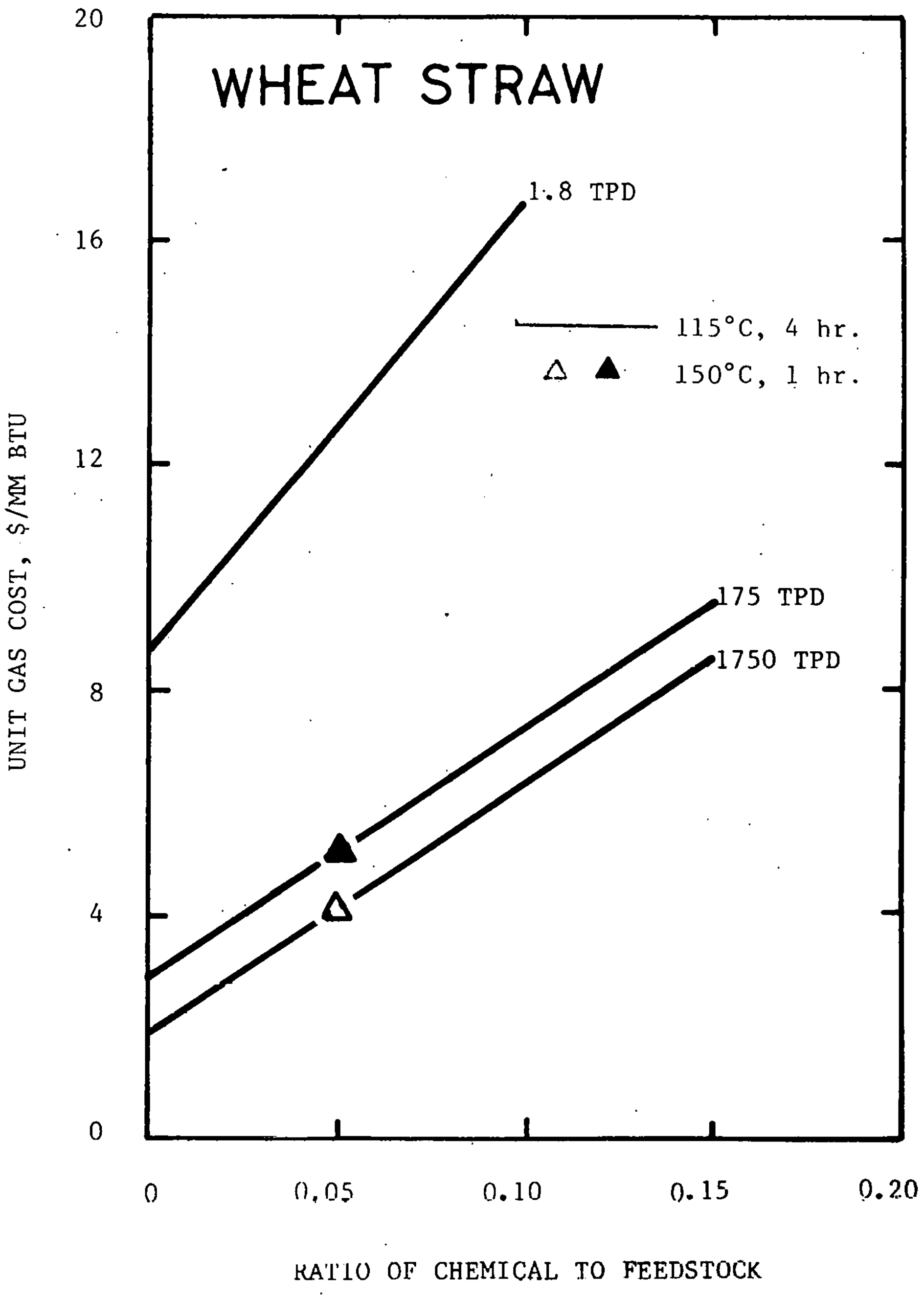


Figure 7.9

EFFECT OF PRETREATMENT ON UNIT GAS COST
WHEAT STRAW



These results indicate that every 1% increase in % chemical requirement adds about $0.50/MM Btu to the gas cost. However, since pretreatment does increase the gas output, the use of about 3% chemical to feedstock ratio will result in the same unit gas cost as the base line system design. Higher chemical requirement will result in greater unit gas costs, and lower chemical requirement would be correspondingly more economical. It is interesting to note that the condition of 0 chemical requirement, which is similar to an autohydrolysis of biomass as investigated by McCarty et al. (Ref. 75), results in a unit gas cost which is about 40% lower than the base line design, assuming no change in the amount converted.

The effect of varying other pretreatment conditions is also shown in Figures 7.7, 7.8, and 7.9 for the medium and large scale systems. The other pretreatment conditions used are 150°C and 1 hour retention time, with 5% chemical added and 50% conversion. The effects of these changes is to lower the capital cost and increase the heat requirement, with the net result of approximately no change in unit gas cost, with an assumed 50% conversion.

The results of this analysis of pretreatment conditions indicates the economic advantages if the assumed conditions can be obtained. Since there is insufficient experimental data to verify such conditions, it is necessary to continue development in this area to provide an economically feasible pretreatment process.

7.3 Gas Purification

The large scale system produces a quantity of gas which could justify delivery to a pipeline system. This would require purification and compression of the digester gas.

Analyses of the large scale systems indicate that gas purification will add about $0.75/MM Btu to the gas cost for corn stover, rice straw, and wheat straw feedstocks. Details of the analysis are presented in Table 7.6 for corn stover. The use of gas purification adds about 15% to the capital cost and about 30% to operating costs, primarily for compression power costs.

Table 7.6

SYSTEM DESIGN FOR DIGESTION OF CORN STOVER UTILIZING GAS PURIFICATION
LARGE SCALE

Table 7.6a

```
                         SYSTEM PERFORMANCE

FEED COMPOSITION

        TOTAL SOLIDS                             2000.0 TONS/D
        SOLIDS FRACTION IN FEED                    .500
        VOLATILE SOLIDS FRACTION IN SOLIDS         .950
        BIODEGR. VOL. SOL. FRACT. IN VOL SOL       .360



STORAGE
        NUMBER OF UNITS                          54.
        CAPACITY PER UNIT                      296296. CU.FT.

SHREDDING
        NUMBER OF UNITS                            7.
        CAPACITY PER UNIT                    .2381E+02 TONS/HR
        POWER REQUIREMENT                        .2500E+04 HP

HOLDING-MIXING

        NUMBER OF UNITS                            3.
        CAPACITY PER UNIT                    .2083E+06 CU FT.
        POWER REQUIREMENT                        .1250E+03 HP

PRETREATMENT-NONE USED

DIGESTION

    CSTR
        NUMBER OF UNITS                          69.
        CAPACITY PER UNIT                    .9964E+05 CU.FT.
        DIGESTER TEMPERATURE                     60.C
        RETENTION TIME                           10.0DAYS
        CONVERSION EFFICIENCY                      .767
        POWER REQUIREMENT                          .1375E+04HP

    GAS PRODUCTION                                1.158 VVD
                                             .7961E+04 MM BTU/D
    HEAT EXCHANGER
        NUMBER OF UNITS                          21.
        HEAT EXCHANGER AREA                  .9533E+04 SQ.FT.

    TOTAL HEAT REQUIREMENT                   .7392E+03 MM BTU/D

DEWATERING-NONE USED
GAS PURIFICATION

        CAPACITY PER UNIT                    .1327E+08 CU.FT./D
```

Table 7.6b

CAPITAL COST ESTIMATE

	MAY 1979 COSTS ($)
INSTALLED EQUIPMENT	
STORAGE UNITS	515741.
SHREDDERS	374715.
HOLDING TANKS	634701.
DIGESTERS	9802033.
HEAT EXCHANGERS	1134220.
GAS PURIFICATION UNITS	2173299.
MATERIALS HANDLING EQUIPMENT	731736.
SUBTOTAL	15366446.
STRUCTURES-ELECT. + PIPING	614658.
SUBTOTAL	15981103.
SUPPORT FACILITIES	799055.
SUBTOTAL CAPITAL INVESTMENT	16780159.
CONTRACTOR OVERHEAD + PROFIT	167802.
ENGINEERING + DESIGN	839008.
SUBTOTAL PLANT INVESTMENT	17786968.
PROJECT CONTINGENCY	2668045.
TOTAL PLANT INVESTMENT	20455013.
INTEREST DURING CONSTRUCTION	1840951.
START-UP COSTS	1237306.
WORKING CAPITAL	409100.
TOTAL CAPITAL REQUIREMENT	23942371.

Table 7.6c

```
                         ANNUAL OPERATING COSTS

                                                    ANNUAL COST ($)


    PRODUCTION MATERIALS

         FEED - $   0.00/TON                                       0.

    UTILITIES

         ELECTRIC - 5.0 CTS./KW-HR                           2345284.

         FUEL   -  $ 5.00/MM BTU                             1517748.

    LABOR

         OPERATING LABOR - MEN PER DAY     24.
                           HRS PER SHIFT    8.0
                           HOURLY RATE    $ 6.00              420480.

         MAINTENANCE LABOR                                    306825.

         SUPERVISION                                          109096.

    ADMINISTRATION + OVERHEAD                                 501841.

    SUPPLIES

         OPERATING                                            126144.

         MAINTENANCE                                          306825.

    LOCAL TAXES + INSURANCE                                   552285.
                                                    --------------------
GROSS ANNUAL OPERATING COST                                  6186528.

    CREDITS/PENALTIES COST                                         0.
                                                    --------------------
NET ANNUAL OPERATING COST                                    6186528.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XX                                                                    XX
XX          TOTAL ANNUAL CAPITAL REQUIREMENT = $    9154430.          XX
XX                                                                    XX
XX          TOTAL ANNUAL GAS PRODUCTION =   2615117. MM BTU           XX
XX                                                                    XX
XX          UNIT GAS COST = $   3.50/MM BTU                           XX
XX                                                                    XX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
              DISCOUNTED CASH FLOW METHOD
   RETURN ON           UNIT GAS COST
   INVESTMENT           ($/MM BTU)

       .10                  3.94
       .15                  5.44
       .20                  6.61
```

7.4 Labor Cost

Operating labor costs contribute about 25 and 10% to the operating costs for the medium and large scale systems. In addition, other factors such as supervision, overhead, and supplies are directly related to operating labor costs which would double the percentage contributions associated with operating labor. For the small farm system, these labor and associated costs were assumed to be zero.

Since labor costs are such a significant factor, it is essential to determine the effects of varying the labor requirements and associated costs. The results of this analysis are presented in Figure 7.10, 7.11, 7.12.

For the small scale system, the base line case utilized $0/hr for the farmer's labor cost. However, this labor could be utilized for another farm operation which is profitable and should be assigned a value. The value of a farmer's labor is extremely difficult to assess, since it is very seasonal. Obviously, during harvesting the labor cost is high and mid-winter it would be low. The effect of labor cost is shown in Figure 7.10, assuming $6/hr average cost, and varying the labor requirement for the digestion process. (The results in this figure can also be used to determine the effect of different average hourly labor rates, e.g., 2 hrs/day at $6/hr would give the same cost as 1 hr/day at $12/hr.) For 1 hr/day labor requirements at $6/hr, the gas cost will increase by $1.50/MM Btu and for 2 hr/day the cost will increase by $3/MM Btu.

The results for the medium size system are presented in Figure 7.11. A variation in operating labor requirement is shown, from the base line case of 4 men/shift to 1 man/shift. The unit gas cost is reduced by about $0.40/MM Btu for each man/shift reduction in labor requirements.

For the large scale system, the base line case utilized 8 men/shift. The results of varying this labor requirement, presented in Figure 7.12, are that a reduction of 1 man/shift reduces the unit gas cost by about only $0.05 MM/Btu.

Figure 7.10

EFFECT OF LABOR REQUIREMENTS ON UNIT GAS COST
SMALL SCALE

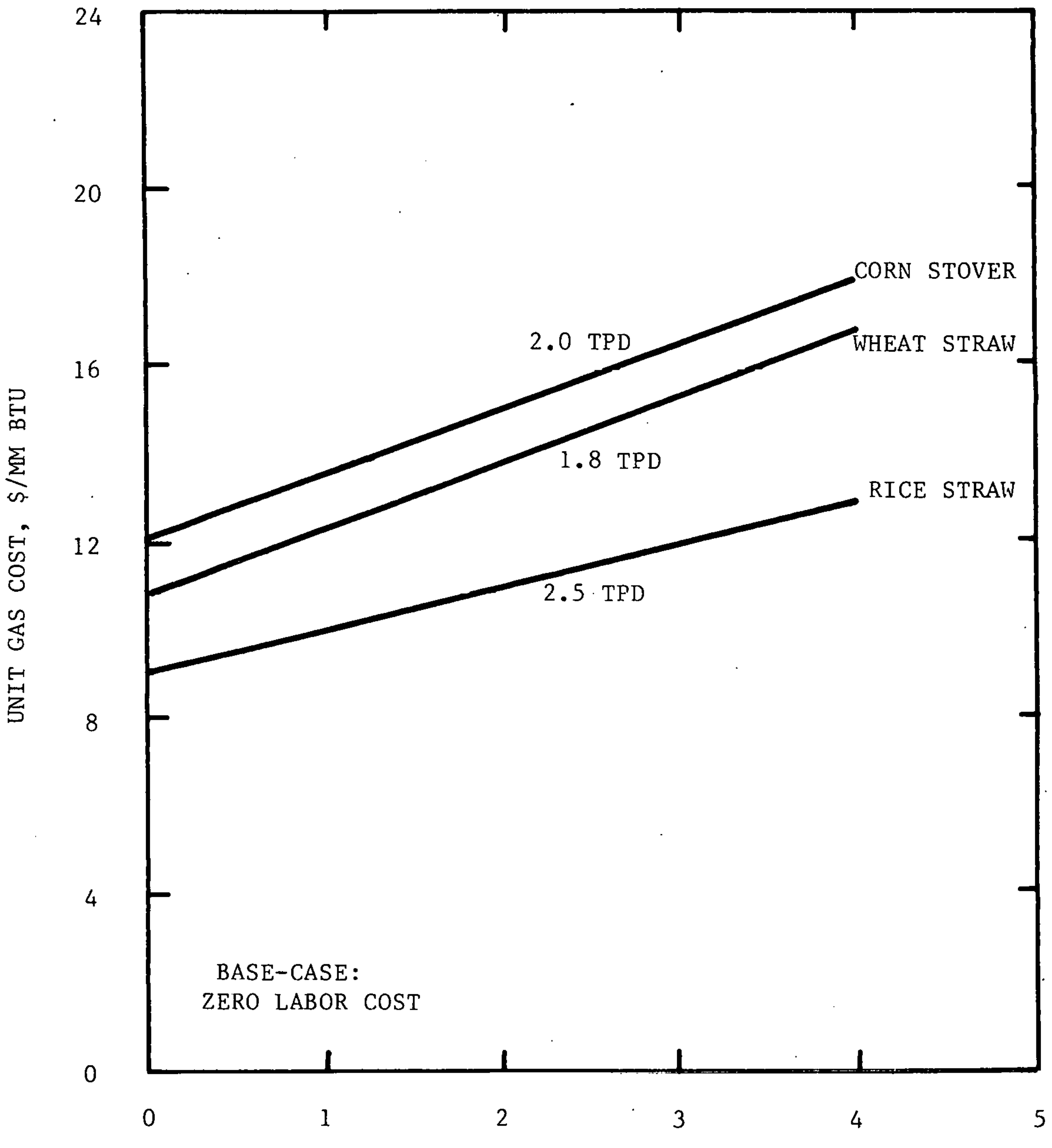


Figure 7.11

EFFECT OF LABOR REQUIREMENTS ON UNIT GAS COST
MEDIUM SCALE

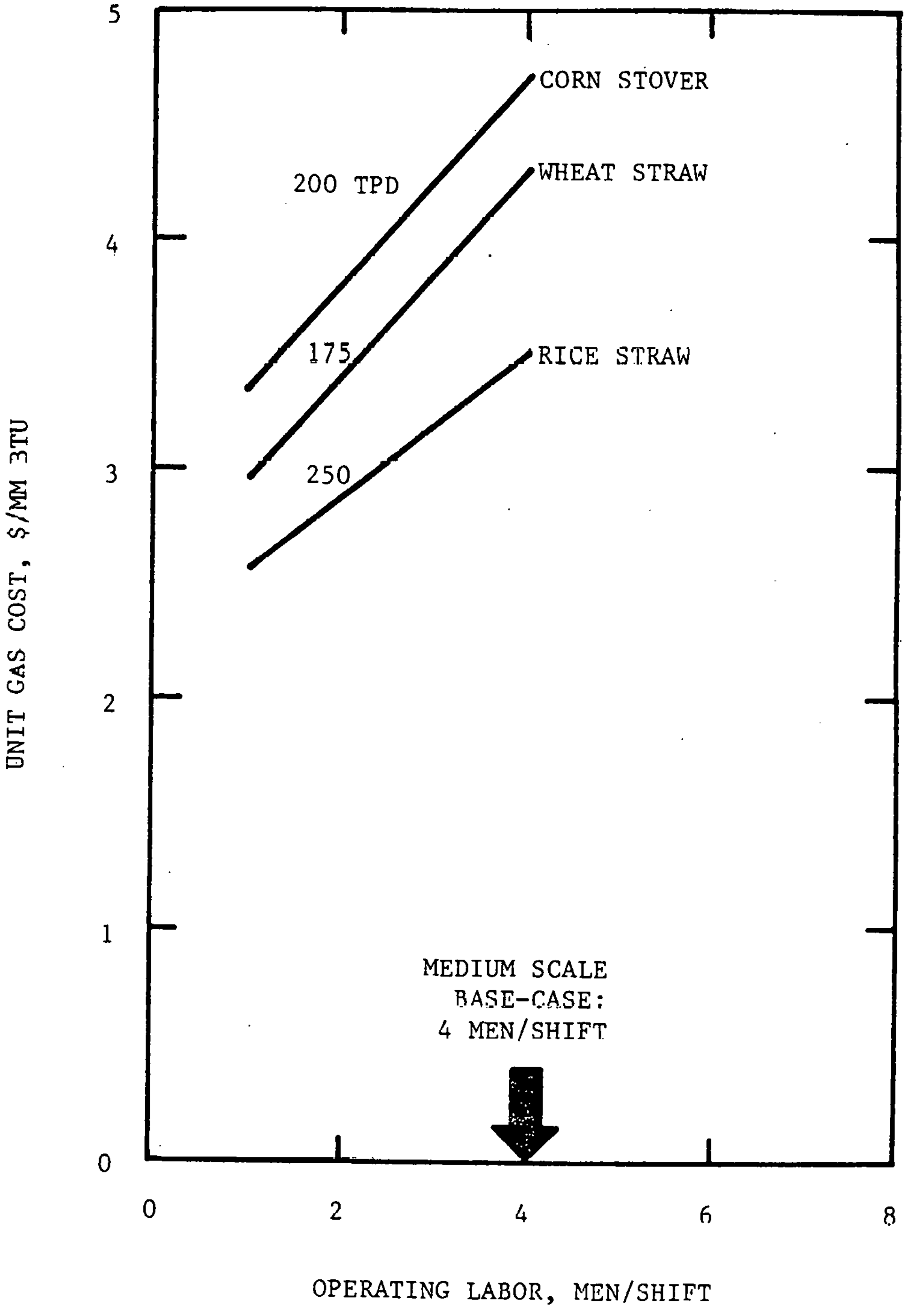
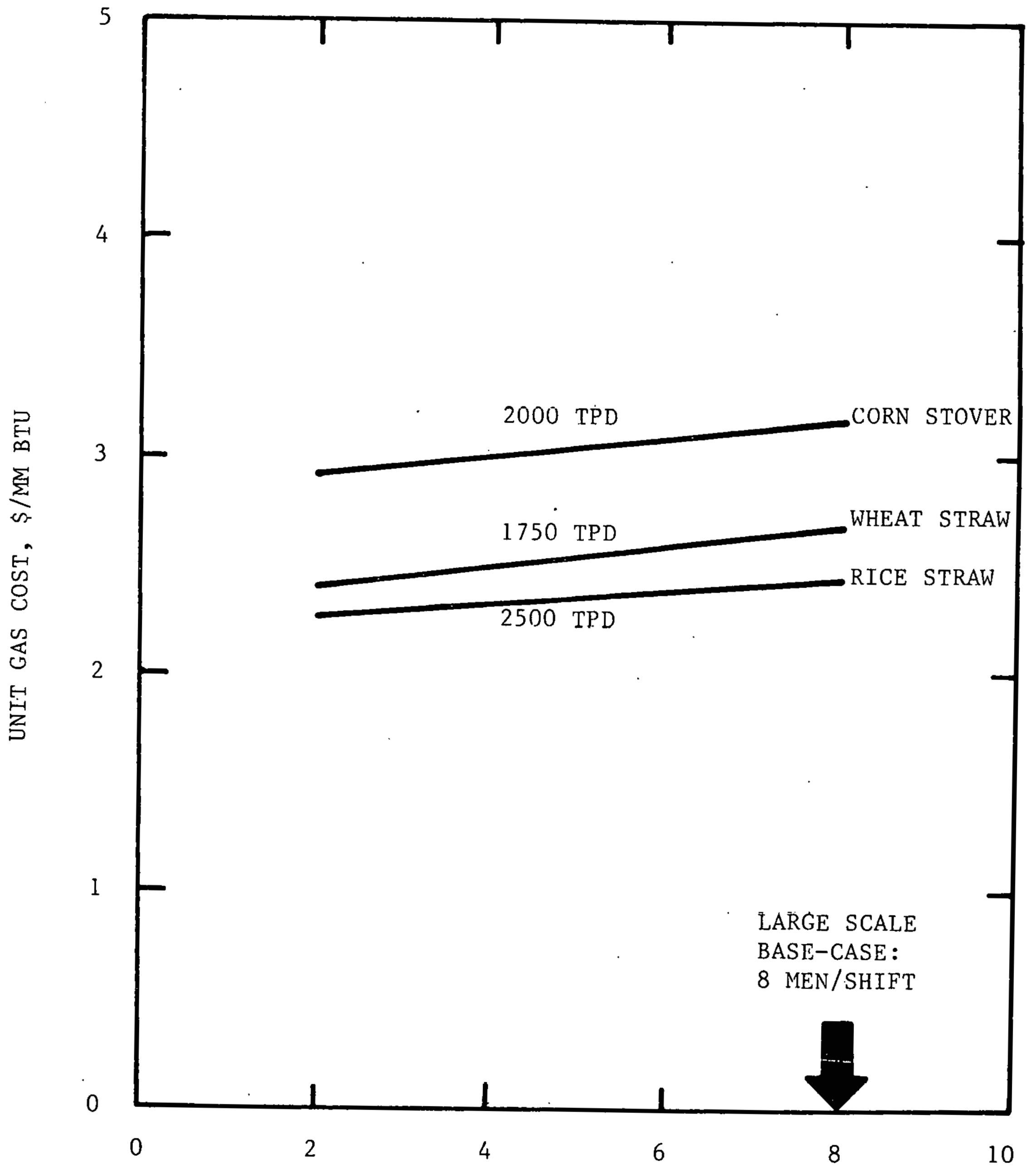


Figure 7.12

EFFECT OF LABOR REQUIREMENTS ON UNIT GAS COST
LARGE SCALE



OPERATING LABOR, MEN/SHIFT

It is concluded from these results that simple digestion systems which require minimal operating labor is essential for an economically feasible process, particularly for the small and medium scale systems. The manpower required for loading feedstock for a continous digestion process would make any reduction in labor requirement very difficult to justify.

7.5 Feedstock Cost

The base line system analysis utilized a $0/ton residue cost. For some biomass sources (e.g., municipal solid waste) drop charges, or negative feedstock costs, are the case, but for agricultural crop residues, it is most likely that a positive cost will be attributed to the feedstock. This cost will be due to removal or harvesting the crop residue from the field, and then delivery to the processing facility.

The effects of feedstock cost on unit gas cost is presented in Figures 7.13, 7.14, and 7.15 for corn stover, rice straw, and wheat straw, respectively. For the medium and large scale system, unit gas cost will increase by $2.50/MM Btu for every $10/ton increase in feedstock cost. For the small scale system, the increase is about $4.00/MM Btu per $10/ton increase in feedstock cost. It should be noted, however, that if pretreatment were used, the gas production would be about doubled, resulting in a sensitivity to feedstock cost of about half of the no pretreatment case.

These results presented in Figures 7.13 - 7.15 must be compared with estimated costs for agricultural crop residue collection and delivery. Approximate costs for crop residues have been developed by SRI International (Ref. 1). They give $10/dry ton for high moisture crop residues (such as corn stover) and $6/dry ton for low moisture residues (such as rice and wheat straws). Vetter (Ref. 140) estimated the cost of harvesting and transporting corn stover to range from $15-20/dry ton for a range of 175-1000 tons per year. The output from a small farm (400 acres) is approximately 700 tons/year. These costs include amortized costs for farm machinery required for the harvesting procedure. Horsfield and Williams (Ref. 141) estimate the cost of rice straw harvesting to be at least $7/ton and a cost of about $6/ton to transport the straw 10 miles.

Figure 7.13

EFFECT OF RESIDUE COST ON UNIT GAS COST FOR CORN STOVER

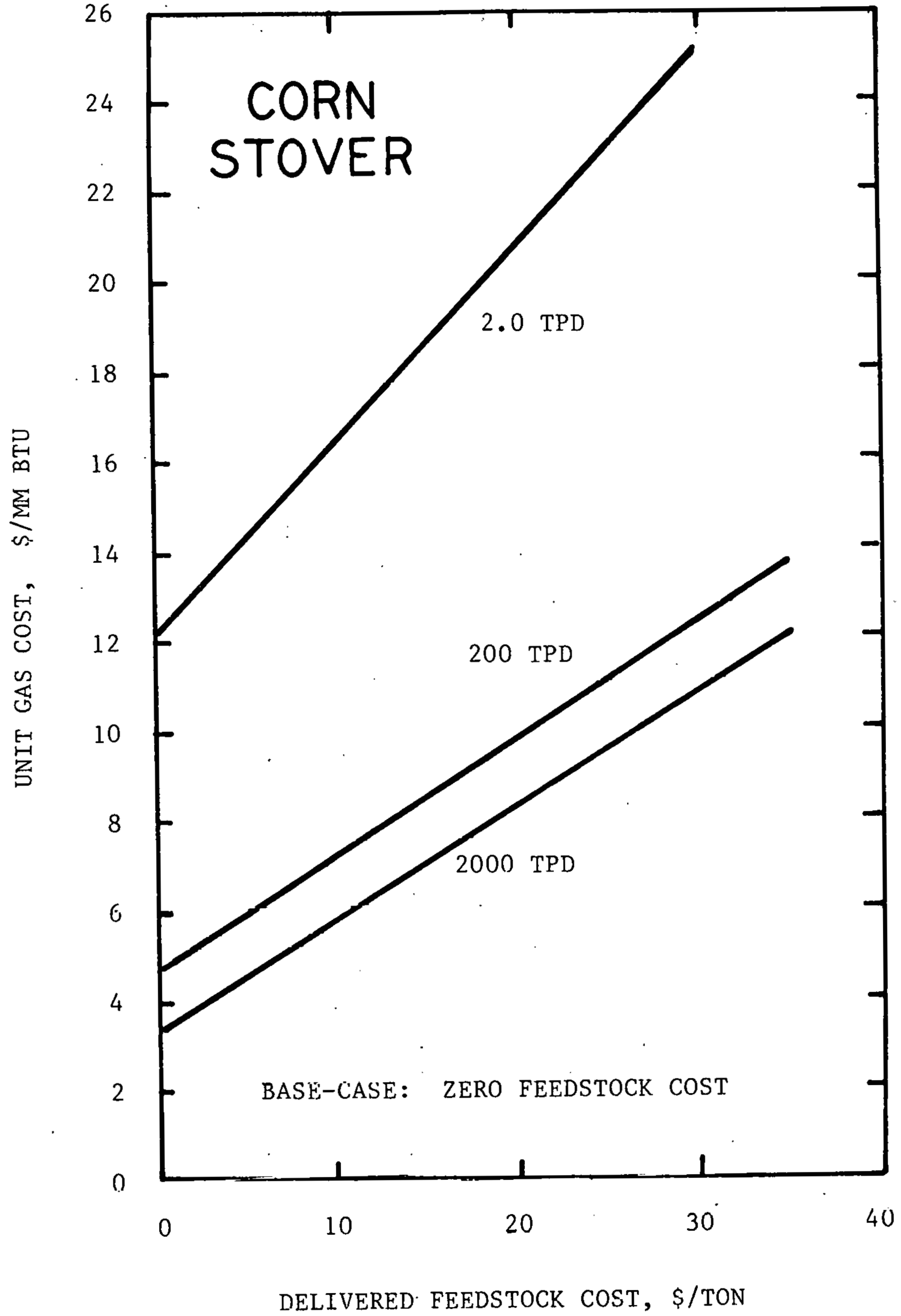


Figure 7.14

EFFECT OF RESIDUE COST ON UNIT GAS COST FOR RICE STRAW

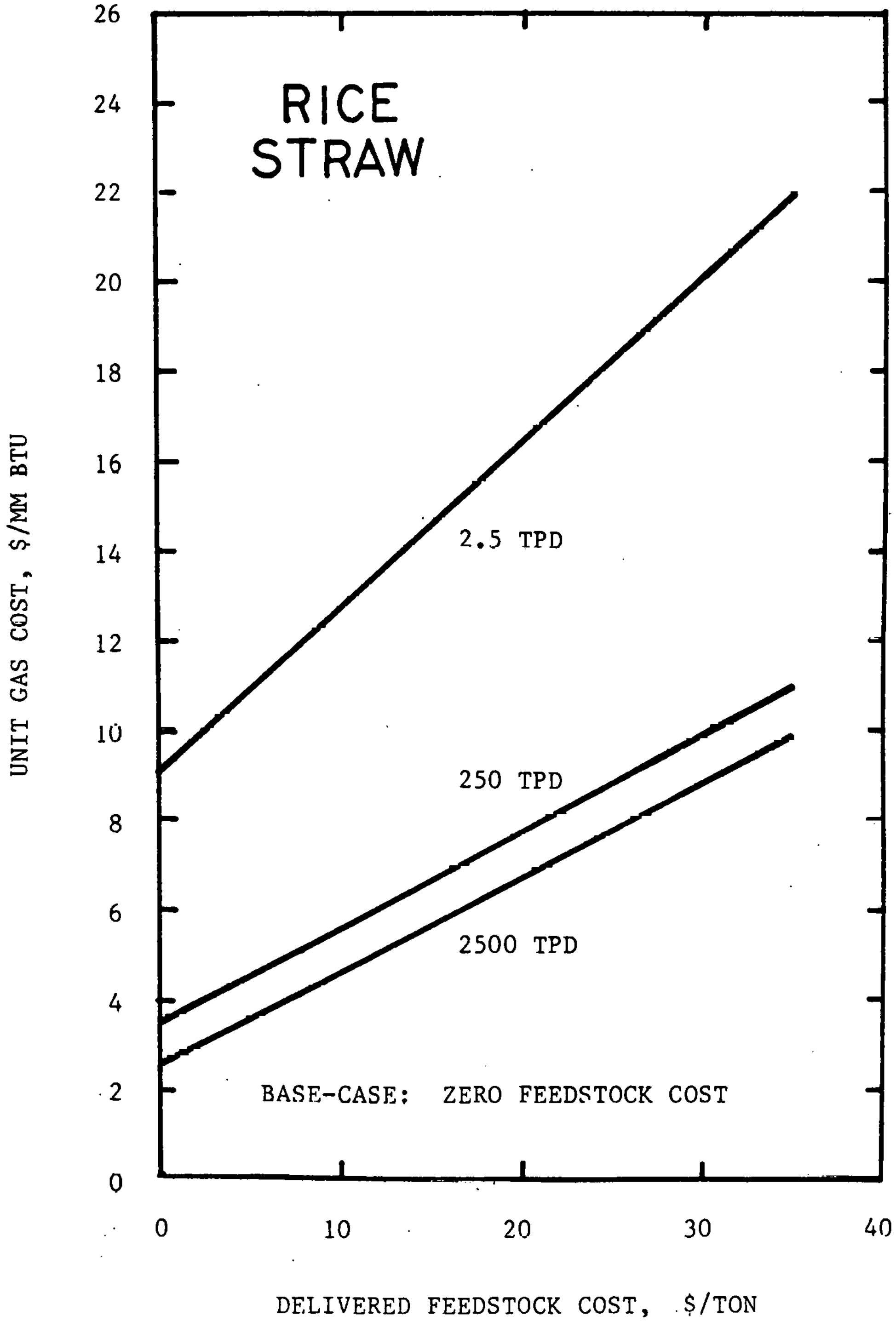
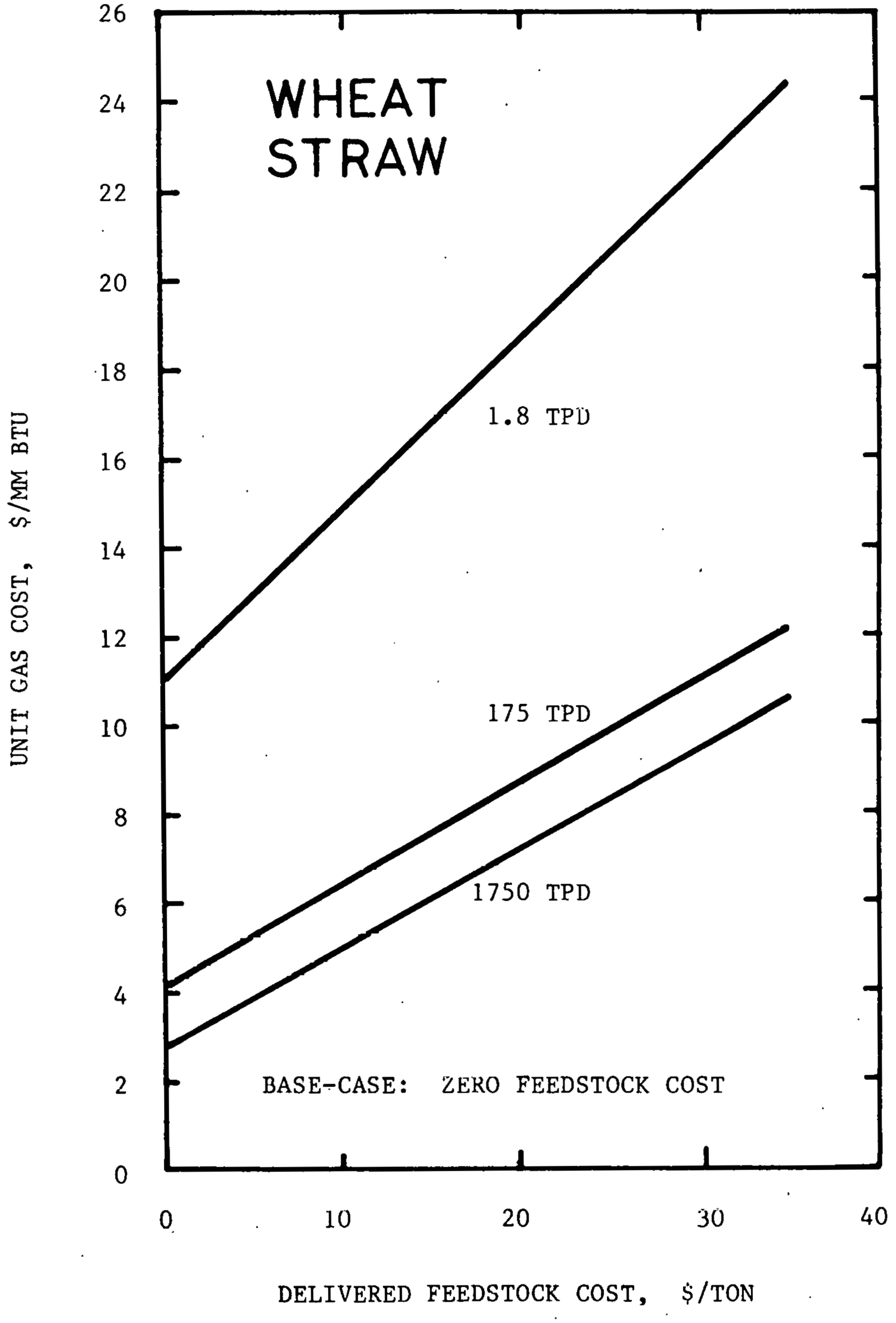


Figure 7.15

EFFECT OF RESIDUE COST ON UNIT GAS COST FOR WHEAT STRAW



The average distance for transportation can be estimated by considering the processing facility is centrally located within the area from which the residue is collected. For the 400 acre small size system, the average distance to transport residue is less than ½ mile. For the cooperative size system, collecting residue from 100 small farms, or 40,000 acres, the average distance is about 10 miles, assuming crop residue is obtained from only 10% of the area around the processing facility. For the large scale facility, the average distance is 30 miles, also assuming collection from 10% of the area. If 25% of the area were harvested, the average distances would be about 6 and 20 miles for the medium and large scale systems, respectively. Thus, for the medium size system, $6/ton for transportation is reasonable. For the large scale system the transportation cost would be about $12/ton, utilizing a cost of about 30¢/mi for the additional distance (Ref. 142).

It is obvious from the range of values presented that the residue cost can range from $5 - 20/ton. The corresponding increases in unit gas cost would range from about $1 -$5/MM Btu for the medium and large scale systems without pretreatment and about $0.50-2.50/MM Btu when pretreatment is utilized. For the small scale system the collection cost would be on the low end (no transportation cost) so this would contribute about $3/MM Btu to the gas cost.

7.6 Credits/Penalties

The base line designs incorporated the assumption that there would be no credit or penalty associated with the digester effluent. Potential uses of the effluent solids include fertilizer and animal feed. The value for such uses could be significant. On the other hand, a penalty could be associated with disposal of digester effluent, particularly the waste water stream after dewatering to recover the solids.

The effect of credits/penalties for the effluent stream was investigated. The conditions utilized in the analysis were a dewatering processing step in which 95% of the solids were recovered at a concentration of 25% solids. The low solids waste stream was disposed at a cost of $2/1000 gal and the credit for the solids ranged from $0 to 75/ton.

The results of this analysis for effects of credits/penalties are presented in Figures 7.16 and 7.17 for corn stover for the medium and large size systems. The results are presented as unit gas cost as a function of DCF return on investment for various effluent solids credit value. For high credit value, the unit gas cost is negative, i.e., a zero present net worth could only be obtained with negative gas value. Since the primary product is to be energy, in the form of gas, negative gas values are meaningless. Another more reasonable approach to analyze these results is to assume a gas value and determine the ROI required to give zero present worth using the DCF method. A gas value of \$2/MM Btu was assumed and is indicated in Figures 7.16 and 7.17 by the horizontal dashed line. The returns on investment obtained by this procedure are presented for each crop residue in Table 7.7 and for corn stover in Figure 7.18. From this figure it is noted that every \$10/ton increase in by-product value increases the return on investment about 4%. These results indicate that if the by-product credit value is high, it will have a greater value than the value of gas. (Under those conditions, it might be better to consider the gas as the by-product stream.)

A comparison should be made between expected by-product credit values and the range of values utilized for the sensitivity analysis. Vetter (Ref. 141) indicates that corn stover would have a fertilizer value of about \$5.00/dry ton. This value is due primarily to the nitrogen, phosphorus and potassium content which would not change significantly during digestion. However, since some biodegradable solids are removed during digestion, the value of the effluent solids would be greater than \$5/ton. Digestion without pretreatment removes about 25% of the total solids, giving an effluent value of about \$6.70/ton. Pretreatment results in about 50% total solids reduction giving an effluent value of about \$10/ton. SRI (Ref. 143) has indicated that a \$25/dry ton value for digested animal manure effluent would be optimistic. The range used in this sensitivity analysis appears to extend to highly optimistic values. The range more probably encountered would be \$5-25/ton, which would give a ROI (assuming \$2/MM Btu gas value) of up to about 10% for the large scale system.

Figure 7.16

EFFECT OF BY-PRODUCT VALUE ON UNIT GAS COST FOR CORN STOVER
MEDIUM SCALE

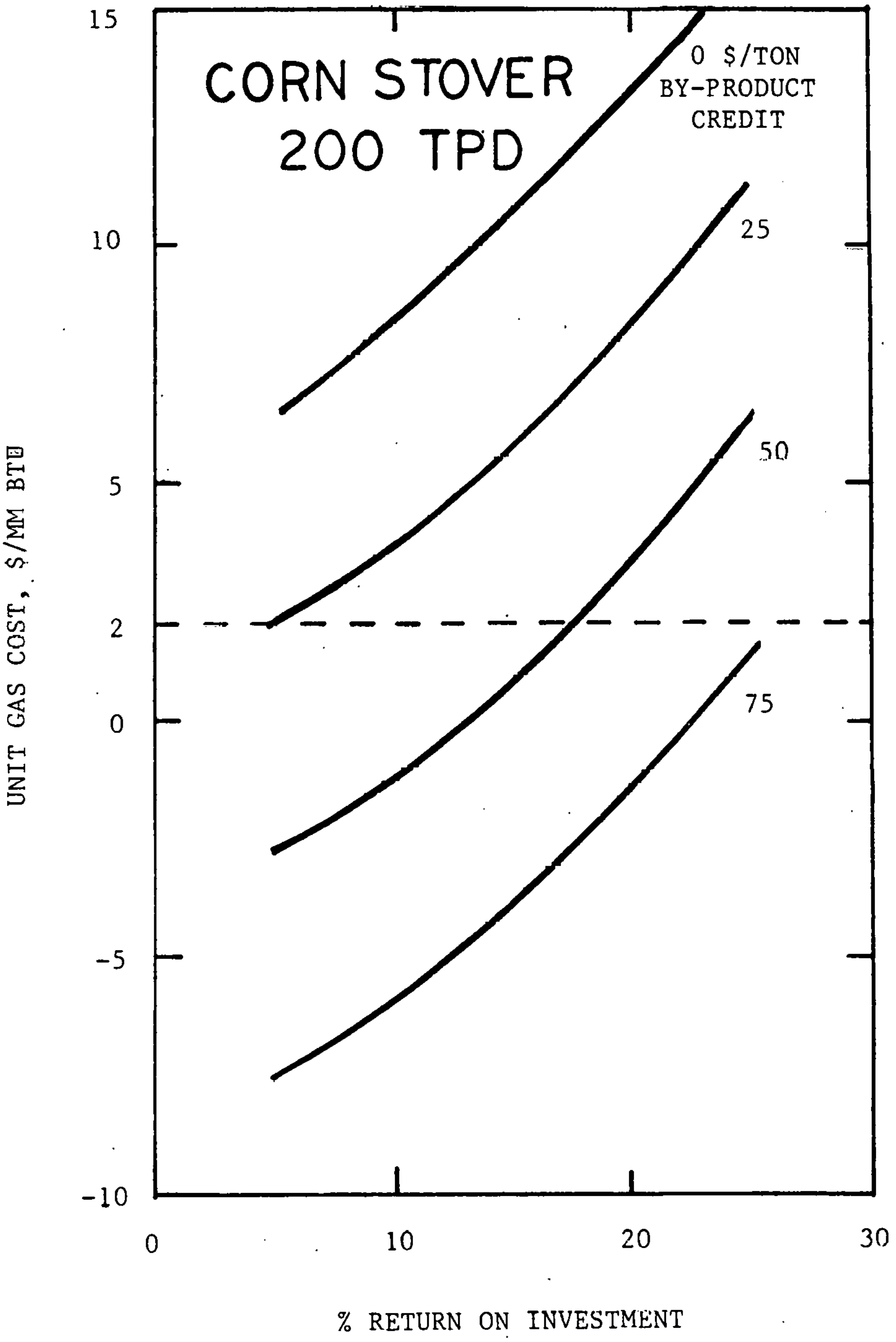


Figure 7.17

EFFECT OF BY-PRODUCT VALUE ON UNIT GAS COST FOR CORN STOVER LARGE SCALE

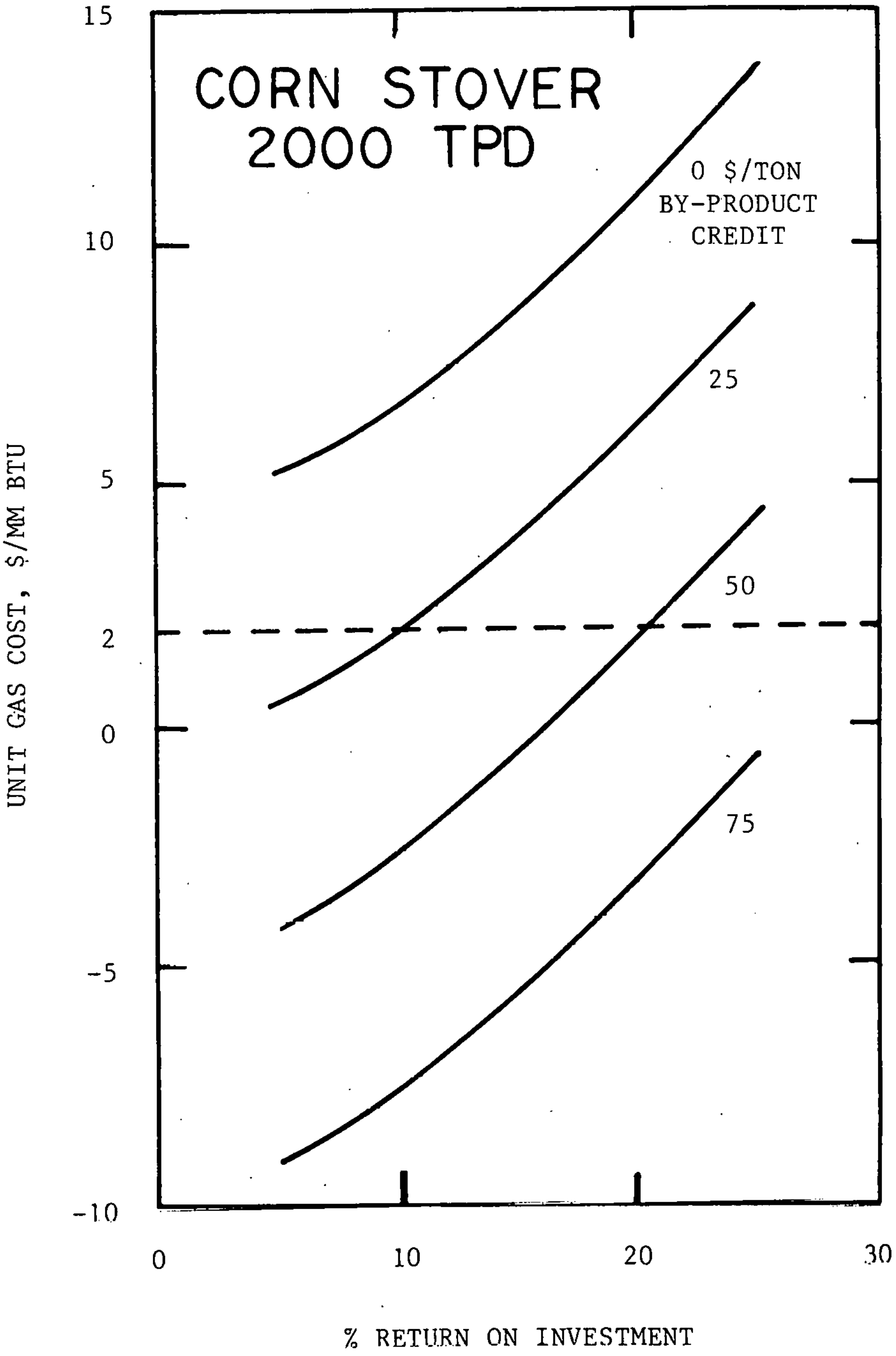


Table 7.7

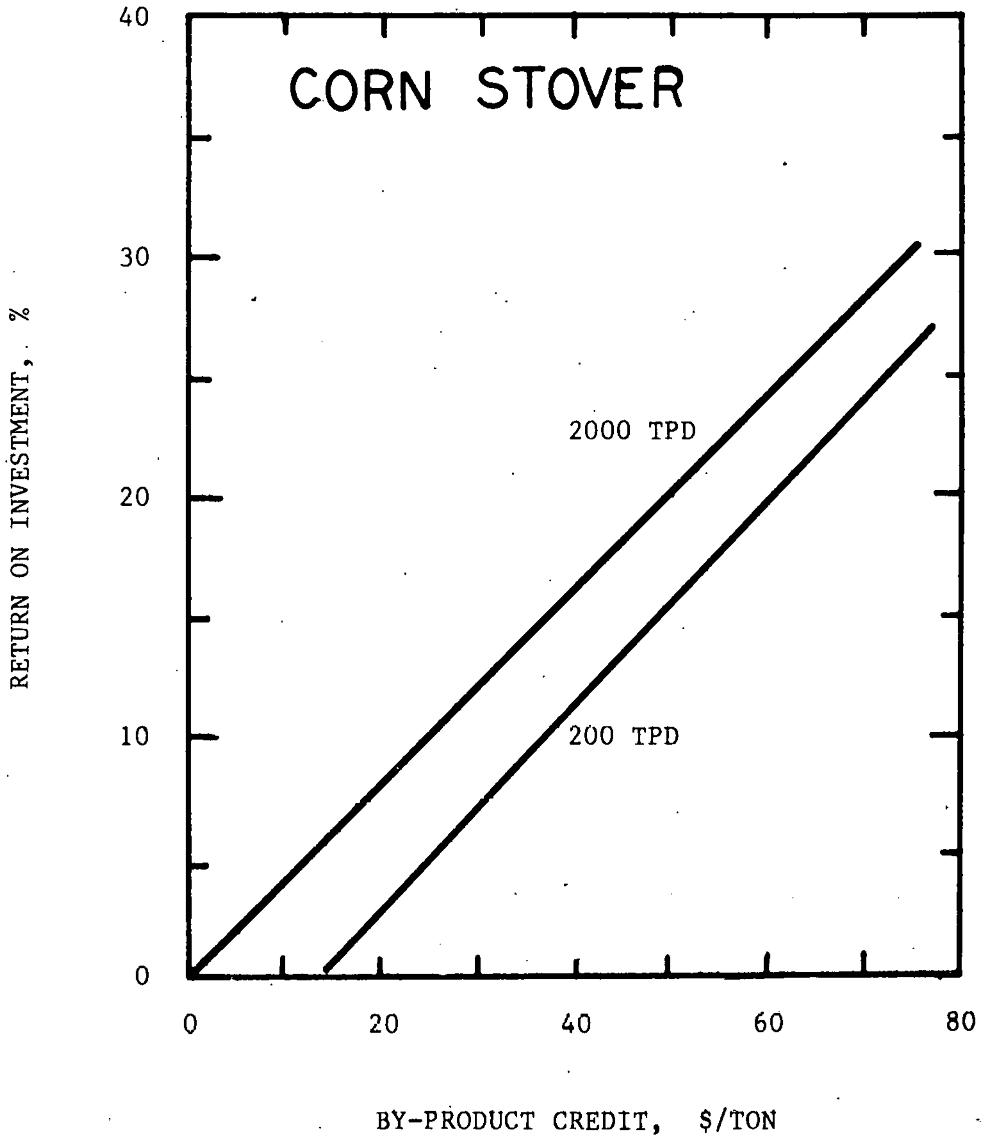
EFFECT OF BY-PRODUCT CREDIT VALUE ON RATE OF RETURN ON INVESTMENT

	% RETURN ON INVESTMENT FOR UNIT GAS COST OF 2 $/MM BTU					
	CORN STOVER		RICE STRAW		WHEAT STRAW	
$/TON BY-PRODUCT CREDIT	200 TPD	2000 TPD	250 TPD	2500 TPD	175 TPD	1750 TPD
0	—	—	—	—	—	—
25	5	10	8	12	4	12
50	16	21	18	22	16	21
75	26	30	26	30	24	30

Figure 7.18

EFFECT OF BY-PRODUCT VALUE ON DCF RETURN ON INVESTMENT

(Gas Value of $2/MM Btu)



7.7 Energy Balance

One of the most critical factors in any alternate energy or energy conversion process is the energy balance, i.e., some indication of the difference between energy in and energy out. There are several ways to define the energy balance. One is the ratio of process energy requirement to gross energy output (the energy content of the digester gas). This can be expressed as:

$$\eta_1 = \frac{\text{annual process energy requirement}}{\text{annual digester gas energy content}}$$

If this ratio were greater than 1, the process would utilize more energy than it delivers and hence would be uneconomical on an energy accounting. It is thus desirable to have a process with as low a value of η_1 as possible.

It should be noted that the definition of η_1 does not incorporate the energy content of the residue feedstock (the higher heating value of the residue). If it is desired to incorporate this energy content into the energy balance, an expression such as given below can be used:

$$\eta_2 = \frac{\text{(digester gas energy content) - (process energy content)}}{\text{(feedstock energy content)}}$$

Thus, for $\eta_1 > 1$, the numerator would be negative, which is an indication that more energy is utilized by the process than is provided. The ratio, η_2, represents the ratio of net energy output to feedstock energy content which is a measure of the process energy efficiency.

Values of these ratios (η_1 and η_2) for the various systems and options are presented in Table 7.8 for corn stover, rice straw, and wheat straw and the small, intermediate, and large scale systems. The energy efficiencies presented in this table indicate that the highest energy efficiency (η_2) occurs for pretreatment followed by continuous thermophilic digestion, i.e., the conditions for the intermediate and large scale systems. These systems also have low values for η_1, the ratio of process energy use to energy output. The

Table 7.8

Energy Efficiency of Crop Residue Digestion Processes

		CORN STOVER			RICE STRAW			WHEAT STRAW		
		small	inter-mediate	large	small	inter-mediate	large	small	inter-mediate	large
Base Line CSTR	η_1	0.49	0.21	0.21	0.35	0.15	0.14	0.40	0.16	0.16
	η_2	0.08	0.21	0.21	0.14	0.30	0.30	0.10	0.24	0.24
Batch Digestion (180d retention time)	η_1	0.08	0.08	0.08	0.03	0.03	0.03	0.04	0.04	0.04
	η_2	0.21	0.21	0.21	0.29	0.29	0.29	0.24	0.24	0.24
CSTR with Pre-treatment	η_1	0.35	0.14	0.14	0.33	0.13	0.12	0.33	0.12	0.40
(5% NaOH, 50% conversion)	η_2	0.17	0.39	0.19	0.19	0.44	0.44	0.18	0.40	0.25
CSTR with Gas Purification	η_1			0.30			0.24			0.25
	η_2			0.18			0.27			0.22

η_1 = (process energy requirement)/ (digester gas of energy content)

$$\eta_2 = \frac{\text{(digester gas energy content) - (process energy requirement)}}{\text{(feedstock energy content)}}$$

lowest values of η_1 arise for the batch digestion process since this design utilizes the heat of reaction to provide process heat and there is no heat loss attributed to the digester effluent stream. Also, the batch system does not require any energy for digester mixing.

7.8 Summary

The results of the sensitivity analysis indicate which parameters significantly affect the system economics. The sensitivity analysis indicates the direction and magnitude of changes which would make the conversion of crop residues to fuel gas economically feasible. In some instances, these changes are to conditions for which no supportive experimental data exist. It is recommended that development of the process be extended to these areas.

Section 8

CONCLUSIONS AND RECOMMENDATIONS

The results of the engineering economic analyses performed on three size systems, small farm, cooperative and industrial scale, utilizing various agricultural crop residues have led to the following conclusions and recommendations. The cost estimates for fuel gas production by a pretreatment/anaerobic fermentation processing route are based on design concepts of DOE Fuels from Biomass contractors. The actual utilization of these processes should be preceded by additional experimental work to determine if the performance parameters utilized in these analyses can be attained.

8.1 Conclusions

1. The average farm size for the total United States is 393 acres.
2. The availability of crop residue for conversion to a fuel gas depends on the efficiency of collection methods, seasonality of the crop, and competition with other end-uses. Currently 75% of residues are returned to the soil for the purposes of fertilizing, conditioning and disposal.
3. Residue yields of small grain straws (wheat straw), corn stover, and large grain straws (rice) are 1.6, 1.75 and 2.3 tons/acre, respectively.
4. The results of the engineering economic analyses indicate that the digestion of unpretreated crop residues is, at best, marginally economical. Digestion of corn stover resulted in the highest gas cost and digestion of rice straw gave the lowest gas cost for all system sizes considered.

5. Batch digestion, utilizing a low cost "hole-in-the-ground" digester, results in higher gas costs than for a continuous process for the cooperative and industrial scale processes. For the small farm system, the batch process if more economical than the continous process and the economics could be improved further if the digester cost were reduced by having the farmer construct the digester.

6. Experimental results indicate that caustic and autohydrolysis pretreatment of crop residue has technical merit. However, there is insufficient data available to warrant a detailed engineering design study.

7. The use of chemical pretreatment will result in a higher unit gas cost, primarily due to the cost of pretreatment chemical. Chemical cost is about 50% of operating cost for medium and large scale systems. Every 1% increase in chemical requirement adds about $0.50/MM Btu.

8. The inclusion of feedstock cost significantly increases the gas cost. The effect is not as severe when pretreatment is employed because the gas production is increased.

9. If a credit value for digester effluent is considered, the economics for the conversion of crop residues become favorable. The value for by-products could be greater than the value of gas produced.

8.2 Recommendations

The results of this study have led to the recommendations to:

1. Continue development of autohydrolysis pretreatment requiring no chemical addition.
2. Continue development of chemical pretreatment with emphasis on lower chemical requirement and/or lower cost chemicals.

3. Develop batch digestion utilizing the controlled landfill concept for small farm digestion of crop residues to fuel gas.

4. Evaluate the fermentation by-products as credits for animal feed or fertilizer in order to determine if the processes are economically feasible.

Since this method is a utility financing method, it is applicable to a utility operation and will be used only for the largest scaled systems considered in this study.

Appendix A
CAPITAL COSTS

Capital costs for equipment are estimated from cost data found in the literature or current costs obtained from equipment manufacturers. The cost relationships presented in this appendix give the cost as a function of equipment size for a base year. Use of the CE plant cost index is utilized to update these costs to May, 1979. This index has a value of 100 for 1957-1959. Values for the CE plant cost index for other years are presented in Table A.1. (Ref. 135).

Table A.1
CE Plant Cost Index

Year	Index Value
1957-1959	100
1967	109.7
1968	113.7
1969	119.0
1970	125.7
1971	132.2
1972	137.2
1973	144.1
1974	165.4
1975	182.4
1976	192.1
1977	204.1
1978	218.8
May 1979	236.2

A.1 Storage

The cost of units for storage of crop residues is estimated to be (on a 1979) cost basis):

$$\text{cost} = 2.65\ (\text{cu. ft.})^{0.54}$$

A.2 Shredder

Shredder costs were obtained from manufacturers' quotes (Williams Patent Crusher and Pulverizer Co., Inc., St. Louis, MO) and the cost relationship is (on a May 1979 basis):

$$\text{cost} = 6400\ (\text{tons/hr})^{0.67}$$

A.3 Holding/Mixing

The cost of holding/mixing tanks, obtained from manufacturer quotes, (Brown Boiler and Tank Works, Franklin, PA) is given by (on a May 1979 basis):

$$\text{cost} = 284\ (\text{cu. ft.})^{0.54}$$

A.4 Pretreatment

Pretreatment will be done at temperatures up to 200°C, thus necessitating the use of pressure vessels. Costs of 150 psi pressure vessels are estimated from manufacturers' quotes (Chicago Bridge and Iron Company, Boston, MA) as (on a May 1979 basis):

$$\text{cost} = 1600\ (\text{cu. ft.})^{0.50}$$

A.5 Digestion

The cost of digesters is dependent on the type of system employed, e.g., a standard high capital cost concrete or steel tank or a low capital cost "hole-in-the-ground" digester used for a batch system. The cost for the high capital digesters is given by the same relationship as for the holding/mixing tanks. This relationship gives a cost of \$98,000 for a 50,000 ft^3 digester compared to \$130,000 for a 50,000 ft^3 digester for the Bartow, FL demonstration facility.

The low capital system cost is dependent on size. Kays (Ref. 144) estimates costs in the range of 2-5¢ per gallon. The lower value will be used for large landfill type systems and is equivalent to approximately $\$4/yd^3$. For smaller hole-in-the-ground systems, the higher value will be utilized. This is equivalent to $\$10/yd^3$.

A.6 Heat Exchangers

The cost of heat exchangers is estimated from Peters and Timmerhaus (Ref. 136) and is given by (on a 1967 basis):

$$\text{cost} = 26\ (ft^2)^{0.75}$$

A.7 Dewatering

Dewatering can be accomplished via centrifugation or vacuum filtration. The cost of centrifugation, obtained from manufacturers' quotes is given by (on a May 1979 basis):

$$\text{cost} = 1960\ (\text{gal/hr})^{0.67}$$

For a liquid stream density of 64 lb/ft^3, this cost can also be given as:

$$\text{cost} = 77{,}000\ (\text{tons/hr})^{0.67}$$

The cost for vacuum filtration is estimated from data provided by Patterson and Banker (Ref. 145) as (on a 1971 basis):

$$\text{cost} = 5500\ (ft^2)^{0.687}$$

If it is assumed that the flux through the filter is 10 gal per hr per ft^2 and density is 64 lb/ ft , the cost is:

$$\text{cost} = 47,900\ (\text{tons/hr})^{0.687}$$

When this expression is updated to May 1979, the cost for a vacuum filter is approximately the same as for a centrifuge when throughputs are equivalent.

A.8 Gas Purification

The cost of gas purification is estimated from Ashare *et al.* (Ref.146) as (on a 1979 basis):

$$\text{cost} = 1000\ (\text{SCFD})^{0.6}$$

where the flow is standard cubic feet of digester gas ($CH_4 + CO_2$) per day.

Appendix B
POWER REQUIREMENTS

B.1 Shredder

The power requirement for shredding is estimated as 15 hp/ton/hr throughput.

B.2 Holding/Mixing

Power will necessary for the holding stage only when mixing will be required. This power requirement is estimated at 0.2 hp/MCF.

B.3 Chemical Pretreatment

The power for chemical pretreatment will depend on whether the process requires mixing. If so, the mixing requirement will be estimated at 0.2 hp/MCF,

B.4 Digestion

The power requirement for digestion will be 0.2 hp/MCF when mixing is utilized.

B.6 Dewatering

The power requirement for dewatering is estimated as 3.15 hp/ton/hr.

B.7 Gas Purification

The power requirement for gas purification is estimated as 300 hp/ MMSCFD.

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Appendix C

MATERIAL BALANCE

Material balances can be made around each piece of equipment for the overall process. These balances will be for solids (total, volatile, biodegradable volatile, and ash), water, gas and total. (The terms used in the equations are the variables used in the computer program.

C.1 Storage

The input and output streams for the storage unit are identical.

C.2 Shredder

The input and output streams associated with the shredder are assumed to be identical. The only change is the size of the particles.

C.3 Holding/Mixing

The holding (and mixing) section is used to prepare the feed material for the pretreatment and/or digestion step. This includes mixing (when necessary) and addition of water to obtain the desired concentration. The material balance is indicated in Figure C.1. The solids concentration in the holding tank is FS1 which is related to the effluent from the holding tank by

$$TF1 = TSF/FS1$$

and the water requirement is

$$WH = TF1 - TFF$$

since only water is added at this step and total solids remain constant.

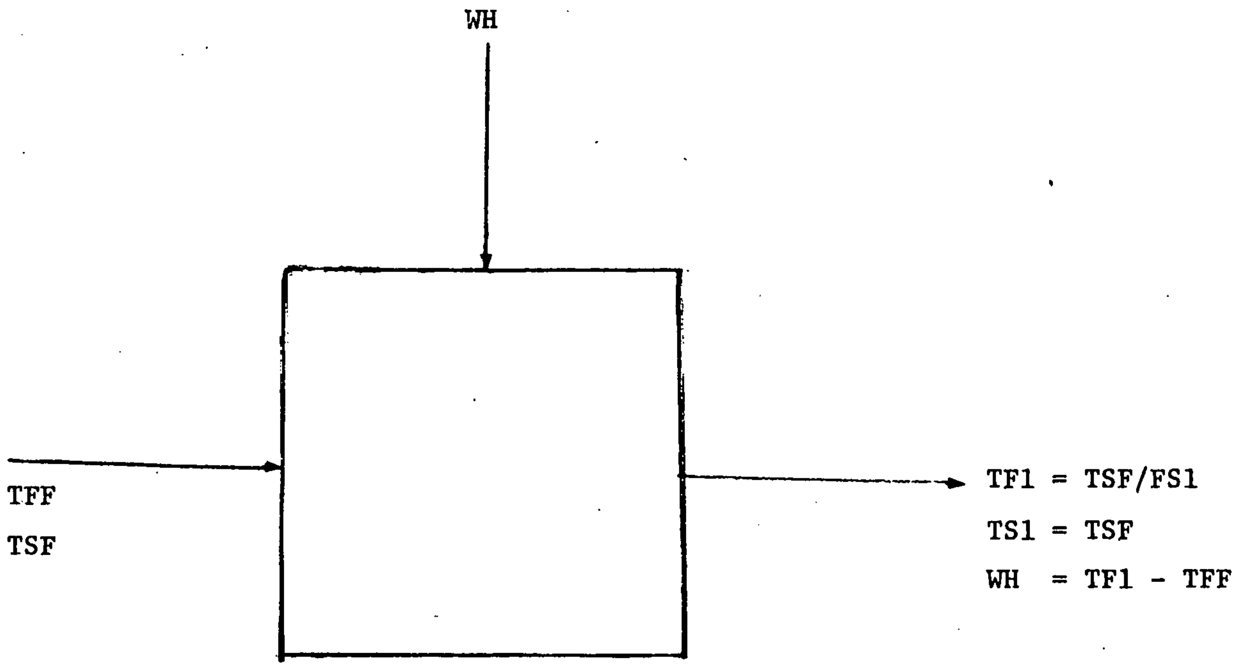


Figure C.1 Material Balance for Holding/Mixing Section

C.4 Chemical Pretreatment

The chemical pretreatment material balance is given in Figure C.2. The amount of non-biodegradable volatile solids converted to biodegradable volatile solids is:

$$TGBVS = EPRT\ (TVSF - TBVSF)$$

where EPRT is the conversion efficiency. The amount of chemical added is assumed to be directly proportional to the amount converted.

$$TCHEM = CHEM\ (TVSF - TBVSF) \times EPRT$$

where CHEM is the amount of chemical required per amount converted. It is assumed that a fraction of the input biodegradable volatile solids is lost in the process:

$$TLBVS = ELPRT \times TBVSF$$

A material balance gives for biodegradable volatile solids:

$$TBVS2 = TBVSF + TGBVS - TLBVS$$

and the total volatile solids is assumed unchanged.

$$TVS2 = TVSF$$

If the fraction of solids leaving the pretreatment reaction is FS2, then:

$$TF2 = TS2/FS2$$

where the total solids is:

$$TS2 = TSF + TCHEM$$

Also, the ash content changes (assuming all TCHEM is ash):

$$TA2 = TAF + TCHEM$$

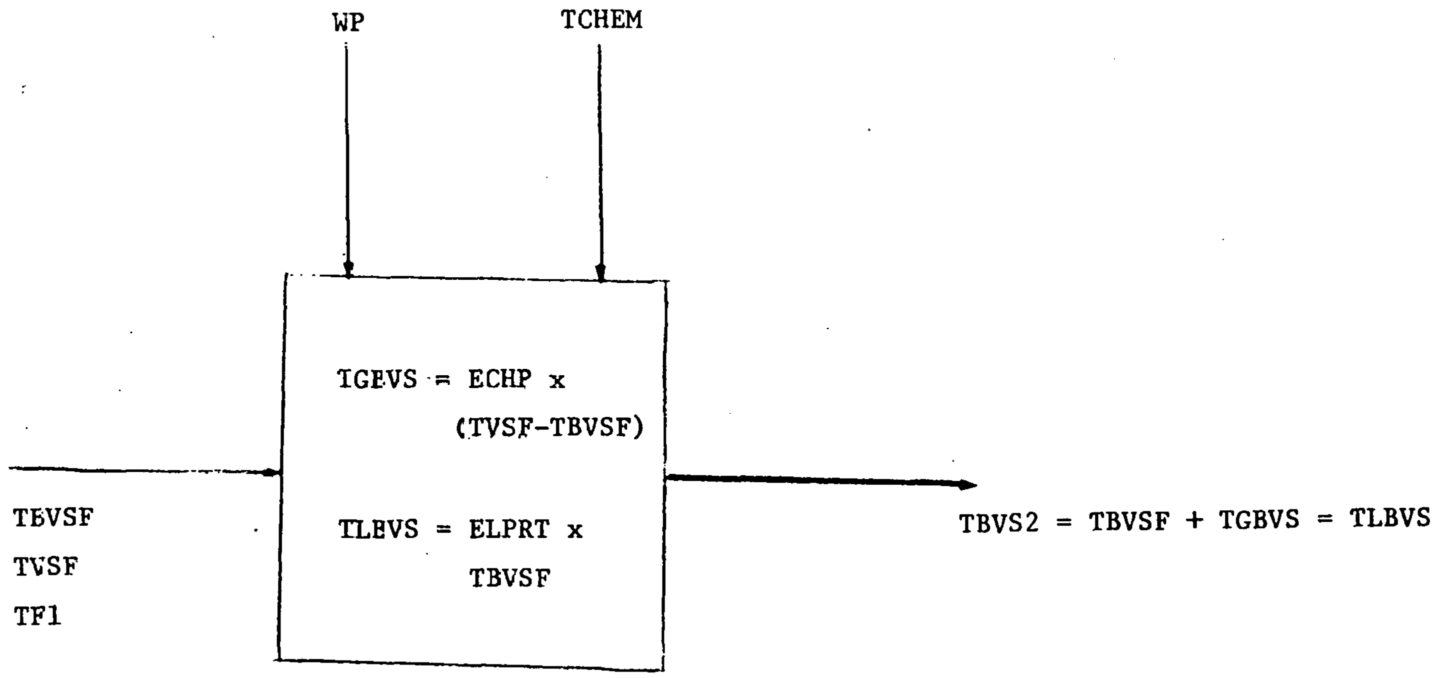


Figure C.2 Pretreatment Material Balance

The water makeup is given by:

WP = TF2 - TF1 - TCHEM

C.5 Digester

The material balance for the digestion step is indicated in Figure C.3. It includes streams for addition of manure (nutrient and inoculum) and water to the digester. This then leads to:

TF3= TF2 + TMAN + WDIG

and corresponding equations for volatile solids, water, etc. Gas is produced in the digestion process, given by:

GPD = A (TBVS3) (FCONV) (DNSDG)/(TF3)(HRTDG)

where FCONV is the fraction of biodegradable solids converted in retention time, HRTDG. DNSDG is the density of the digester contents.

The biodegradable solids leaving the digester is:

TBVS4 = TBVS3 (1-FCONV)

and the total system flow is:

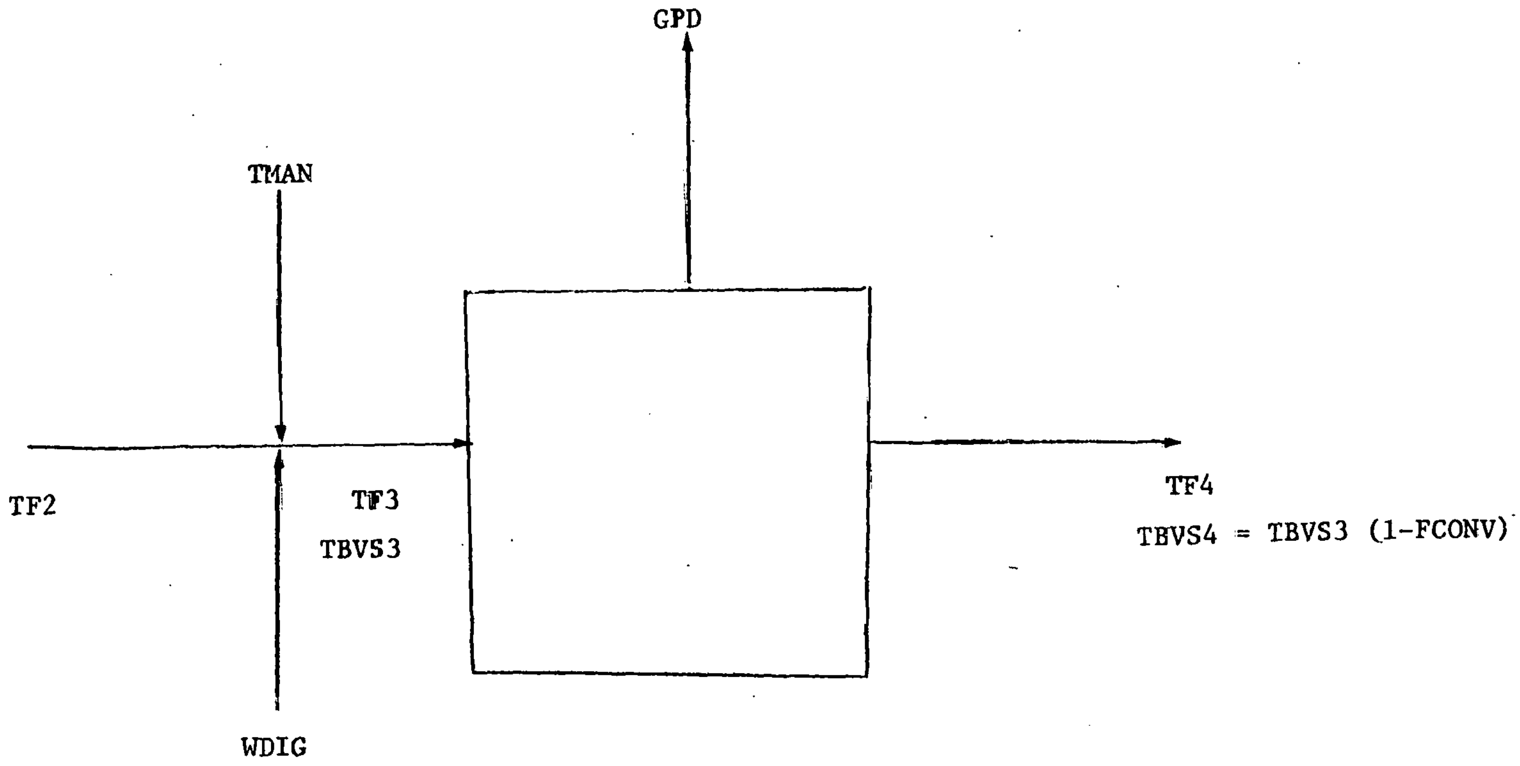
TF4 = TF3 - [H2OEV + (FCONV) (TBVS3)]

C.6 Dewatering

The dewatering unit splits the digester effluent into two streams, as shown in Figure C.4. One is a high solids content stream and the other a low solids content. The efficiency of solids removal is EDWT and the high solids content is FS5 (fraction of solids). Hence,

TS5 = TS4 x EDWT

and the fraction of solids in this stream, FS5, is related to the total



C.3 Digester Material Balance

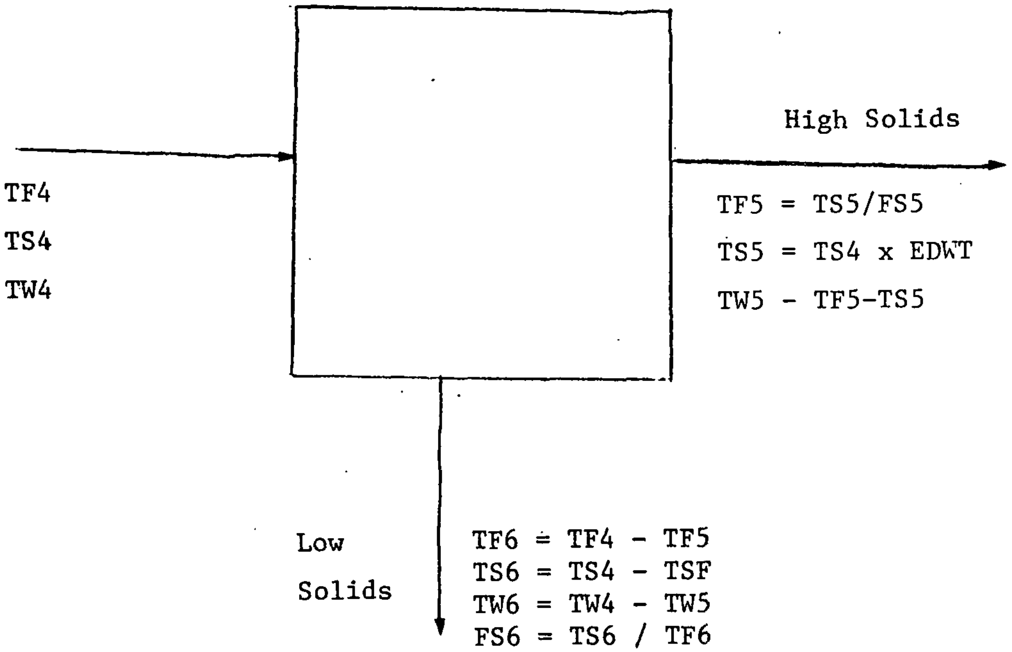


Figure C.4 Dewatering Material Balance

flow by:

$$TF5 = TS5/FS5$$

or

$$TW5 = TS5(1-FS5)/FS5 = TF5 - TS5$$

The low solids stream is as indicated in Figure C.4.

APPENDIX D

Heat Balance

The heat requirements for the system are given by:

$$HREQ = HGAS + HEVAP + HEFF + HLOSS - HFEED - HW - HRXN + 0.01(PRTHT) \quad \text{Btu/d}$$

where

HREQ	is the heat requirement
HGAS	is the sensible heat of the gas stream
HEVAP	is the sensible heat and heat of evaporation of the moisture in the gas stream
HEFF	is the sensible heat of the digester effluent
HLOSS	is the heat loss through the digester walls
HFEED	is the sensible heat of the input stream
HW	is the sensible heat of the water make-up stream
HRXN	is the heat of reaction
PRTHT	is the pretreatment heat requirement.

For this analysis, the ambient or base temperature is TA, the digester temperature is TC, and pretreatment temperature is TMPPR (For these equations, all temperatures are in °C.)

D.1 Input Stream

The sensible heat of the input stream is:

$$HFEED = 3600\ (TF2)\ (TMPF-TA)\ \text{Btu/day}$$

The heat capacity is assumed to be 1 Btu/lb°F. TMPF is the temperature of the feed stream, assumed to be TA.

D.2 Water Make-Up

$$HW = 3600\ (TW2)\ (TMPW - TA)\ \text{Btu/d}$$

where TMPW is the makeup water temperature, assumed to be TA.

D.3 Effluent Stream

The sensible heat of the digester effluent stream is:

$$HEFF = 3600\ TF4\ (TPEX - TA)\ \text{Btu}$$

where TPEX is the exit temperature (either from the digester or heat exchanger) and the heat capacity is assumed to be 1 Btu/lb°F.

D.4 Digester Heat Loss

The heat loss from the digester can be expressed as:

$$HLOSS + U_S A_S\ (TC-TA) + U_B A_B\ (TC-TA) + U_T A_T\ (TC - TA)$$

where the terms on the right hand side represent the loss from the walls, bottom and top respectively. In each case U is the overall heat transfer coefficient and A is the surface area. For a concrete tank with dirt insulation, approximate overall heat transfer coefficients are (Ref. 147):

$$U_S = 0.5\ \text{Btu/hrft}^2{}^\circ\text{F}$$

$$U_B = 0.08\ \text{Btu/hrft}^2{}^\circ\text{F}$$

$$U_T = 0.37\ \text{Btu/hrft}^2{}^\circ\text{F}$$

If the digester is assumed to be cylindrical with equal diameter and height, the digester volume is:

$$V = \pi D^3/4$$

and the surface areas are:

$$A_T = A_B = 0.923\ V^{2/3}$$

$$A_S = 3.69\ V^{2/3}$$

The heat loss is then found to be approximated by:

$$HLOSS = 96.23\ V^{2/3}\ (TC - TA)\ \text{Btu/d}$$

where V is the digester volume (Ft^3) and the temperatures are in °C.

D.5 Gas Stream

The sensible heat loss with the gas stream is made up of contributions from methane, carbon dioxide, and water. The water is included in HEVAP (D.6).

$$\text{Methane Contribution} = DGP \times \frac{16}{370} \times 0.56 \times (TC-TA) \times 1.8$$

$$\frac{ft^3}{d} \quad \frac{lb}{ft^3} \quad \frac{Btu}{lb^\circ F} \quad {}^\circ C \quad \frac{^\circ F}{^\circ C}$$

(Note that a molar volume of 370 ft^3 was used since the gas industry takes STP at 60°F and the gas production was calculated on that basis. The heat capacity of methane is taken as 0.56 Btu/lb°F (Ref. 148).

Hence, the methane contribution is:

$$0.04\ DGP\ (TC - TA)$$

The CO_2 contribution is found to be (assuming the CH_4:CO_2 ratio of 6:4) with $C_{p,\ CO_2}$ = 0.215/Btu/lb°F (Ref. 148) or:

$$0.02\ DGP\ (TC - TA)$$

Thus,

$$HGAS = 0.072\ DGP\ (TC - TA)\ \text{Btu/d}$$

D.6 Evaporated Water

The heat loss due to evaporated water is due to the sensible heat loss of the stream and heat of evaporation of water. The amount of water evaporated is dependent on temperature and is calculated assuming the gas stream is saturated with water at digester temperature.

$$HEVAP = H2OEV\ [\Delta H_{VAP} + C_P\ (TC - TA)]$$

$$HEVAP = H2OEV\ [1025 + 0.805\ (TC - TA)]\ \text{Btu/d}$$

where H2OEV is the amount of water evaporated (lb/d).

The amount of water leaving the digester by evaporation is:

$$H2OEV = 0.0474\ (DGP)\ (XX)\ /\ (1 - XX)\ \text{lb/d}$$

where XX is the mole fraction of water (assuming saturation) given by:

$$XX = 1.27 \times 10^6 \exp\ [-5220/(TC + 273.16)]$$

D.7 Heat of Reaction

For the digestion of biomass to methane the reaction is exothermic.

For:

$$\text{cellulose} + H_2O = 3CH_4 + 3CO_2$$

the heat of reaction is:

$$\Delta H_R = 3\ (\Delta H_{F,\ CH_4} + \Delta H_{F,\ CO_2}) - \Delta H_{F,\ H_2O} - \Delta H_{F,\ \text{cellulose}}$$

where the ΔH_F's are the heats of formation. These are (Ref 148):

$\Delta H_{F,\ CH_4} = 20.3$ kcal/mol

$\Delta H_{F,\ CO_2} = 94.4$

$\Delta H_{F,\ H_2O} = 68.4$

The heat of formation of cellulose can be obtained from the heat of combustion, which is 671 kcal/mole (Ref. 149):

$$\text{cellulose} + 6O_2 = 6CO_2 + 5H_2O$$

$$\Delta H_{comb} = 6\Delta H_{F,\ CO_2} + 5\Delta H_{F,\ H_2O} - \Delta H_{F,\ cellulose}$$

from which $\Delta H_{F,\ cellulose}$ is 237.4 kcal/mol. The heat of reaction is 38.3 kcal per mole reacted or approximately 13 kcal per mole of methane produced. This is approximately 61.6 Btu/ft^3. The heat produced by the reaction in the digester is :

HRXN = 61.6 DGP Btu/d

D.8 Pretreatment Heat Requirement

The heat requirement for pretreatment is due primarily to the difference in sensible heats between the influent and effluent streams of the pretreatment unit. This is given by:

PRTHT = 3600 TF2 (TMPPR - TPF) Btu/d

where TPF is the temperature of the feed stream leaving the heat exchanger. For the energy balance, it is assumed that 90% of this sensible heat can be recovered via use of heat exchange. Hence the contribution to the overall heat balance is:

0.1 PRTHT Btu/d

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Appendix E

```
      PROGRAM BIOGAS4(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)

      DIMENSION ACP(10),          TNMBR(10),WK(10),CONS(10),EX(10),OIND(10
     1),CCOS(10),TCOS(10)
      READ(5,96)K
      READ(5,96)KK
      READ(5,95)(CONS(I),I=1,KK)
      READ(5,95)(EX(I),I=1,KK)
      READ(5,95)(OIND(I),I=1,KK)
      READ(5,95)OINDX,PPMP,PSEP,PSF,PUOP,PED,PPC,PIDC,PWC,STF,EFFS,AW,
     1PM,PSV,PAH,POPS,PLTI,PSUP,OIP,RE,FDBT,FITR,CEP,CST,EA,
     1       FMAN,FSM,FVSM,FBVSM,WD,      CEFV,CDWV,         CF,HTC,TA,A,FS5,
     2SHRMC,SHRWK,STRMC,HEXMC,HLDMC,PRTMC,DWTMC,DWTWK,EDWT,GPUWK,DNSTR,
     3DLIFE
   95 FORMAT(F20.0)
   96 FORMAT(I3)
      READ(5,95)CPF,CCHM,PKC,ELPRT,EPRT,PRTWK,HRTPR,HRTST,HRTHL,HLDWK,
     1DNSHL,DNSPR,CHEM,FS1,FS2,FS3,HRTDG,DIGMC,DIGWK,DNSDG,BLDT,TC
      READ(5,95)DPPC,CONS(5),EX(5),OIND(5),TMPPR
      READ(5,96)INSHR,INHLD,INPRT,INSTR,INHEX,INDIG,INDWT,INGPU
      DO 99 JJ=1,K
      READ(5,95)FD,FSF,FVSF,FBVSF,TMP
      DO 77 J=1,KK
   77 ACP(J)=1.E-8
      CHEM=0.


C     FEED COMPOSITION

      TSF=FD
      TNDO=365.*STF
      IF(INDIG)1,1,2
    2 TSF=TSF*365./BLDT
      TNDO=BLDT
    1 TFF=TSF/FSF
      TVSF=TSF*FVSF
      TBVSF=TVSF*FBVSF
      TAF=TSF-TVSF
      TWF=TFF-TSF

C     STORAGE

      IF(INSTR)11,11,12
   12 NSTR=TSF*2000.*HRTST/(DNSTR*STRMC)
      TNMBR(1)=1.+NSTR
      ACP(1)=TSF*2000.*HRTST/(DNSTR*TNMBR(1))
      GO TO 13
   11 TNMBR(1)=0.
   13 WK(1)=0.

C     SHREDDING

      IF(INSHR)15,15,16
   16 NSHR=TFF/(SHRMC*24.)
      TNMBR(2)=1.+NSHR
      ACP(2)=TFF/(TNMBR(2)*24.)
      WK(2)=TNMBR(2)*ACP(2)*SHRWK
```

```
      GO TO 20
   15 TNMBR(2)=0.
      WK(2)=0.

C     HOLDING/MIXING

   20 IF(INHLD)21,21,22
   22 TF1=TSF/FS1
      WH=TF1-TFF
      IF(WH)23,23,24
   23 WH=0.
      FS1=FSF
   24 NHLD=TF1*2000.*HRTHL/(DNSHL*HLDMC)
      TNMBR(3)=1.+NHLD
      ACP(3)=TF1*2000.*HRTHL/(DNSHL*TNMBR(3))
      IF(INHLD)25,25,26
   26 WK(3)=TNMBR(3)*ACP(3)*HLDWK
      GO TO 27
   25 WK(3)=0.
      GO TO 27
   21 TF1=TFF
      FS1=FSF
      WH=0.
      TNMBR(3)=0.
      WK(3)=0.
   27 TW1=TWF+WH

C      PRETREATMENT (CHEMICAL/THERMAL)

      IF(INPRT)31,31,32
   32 TGBVS=(TVSF-TBVSF)*EPRT
      TCHEM=CHEM*TSF
      TLBVS=TBVSF*ELPRT
      TBVS2=TBVSF+TGBVS-TLBVS
      TS2=TSF+TCHEM
      TA2=TAF+TCHEM
      TVS2=TVSF
      TF2=TS2/FS2
      WP=TF2-TF1-TCHEM
      IF(WP)33,33,34
   33 WP=0.
      FS2=FS1
      TF2=TS2/FS2
   34 TW2=TW1+WP
      NPRT=TF2*2000.*HRTPR/(DNSPR*24.*PRTMC)
      TNMBR(4)=1.+NPRT
      ACP(4)=TF2*2000.*HRTPR/(DNSPR*24.*TNMBR(4))
      WK(4)=TNMBR(4)*ACP(4)*PRTWK
      GO TO 39
   31 TCHEM=0.
      TBVS2=TBVSF
      TS2=TSF
      TA2=TAF
      TF2=TF1
      TVS2=TVSF
      TW2=TW1
      WP=0.
```

```
      FS2=FS1
      TNMBR(4)=0.
      WK(4)=0.
      PRTHT=0.
      TMPPF=TA
   39 CONTINUE

C       DIGESTION

C      RATE CONSTANT

      RK=RKO*EXP(-EA/(1.987*(TC+273.16)))
      TMS=TS2*FMAN
      TS3=TMS+TS2
      TVS3=TVS2+TMS*FVSM
      TBVS3=TBVS2+TMS*FVSM*FBVSM
      TA3=TA2+TMS*(1.-FVSM)
      TF3=TS3/FS3
      TMW=TMS*(1.-FSM)/FSM
      WDIG=TF3-TF2-TMS/FSM
      IF(WDIG)44,44,45
   44 WDIG=0.
      TF3=TF2+TMS/FSM
      FS3=TS3/TF3
   45 TW3=TW2+WDIG+TMW
      CBI=TBVS3/TF3*DNSDG
      IF(TNDIG)51,52,59

C      CSTR

   51 CBE=CBI/(1.+RK*HRTDG)
      GO TO 55
   52 CBE=CBI*EXP(-RK*HRTDG)
   55 TVD=TF3*2000.*HRTDG/DNSDG
      GO TO 58

C      BATCH

   59 CBE=CBI*EXP(-RK*HRTDG)
      TVD=TF3*2000.*BLDT/DNSDG
   58 NDIG=TVD/DIGMC
      TNMBR(5)=1.+NDIG
      ACP(5)=TVD/TNMBR(5)
      WK(5)=TNMBR(5)*ACP(5)*DIGWK
      FCONV=(CBI-CBE)/CBI

C      GAS PRODUCTION

      IF(TNDIG)53,53,54
   53 GPD=A*(CBI-CBE)/HRTDG
      DGP=GPD*TVD
      DCHMC=0.
      GO TO 40
   54 BGP=TBVS3*2000.*A*BLDT*FCONV
      DGP=BGP/HRTDG
      GPD=DGP/TVD
      DCHMC=0.01*TS3*TNDO*30.
```

```
C       DIGESTER HEAT EXCHANGER

    40 IF(INHEX)41,41,42
    42 TPEX=(TC-TA)*0.1+TA
       XX=1.27E6*EXP(-5220./(TC+273.15))
       H2OEV=DGP*XX/(1.-XX)*0.0474
       TF4=TF3-(H2OEV/2000.+(CBI-CBE)/DNSDG*TF3)
       TPF=TF4*(TC-TPEX)/TF2+TA
       TAHEX=TF4*2000.*CF*(TC-TPEX)/((TPEX-TA)*HTC*24.)
       NHEX=TAHEX/HEXMC
       TNMBR(6)=1.+NHEX
       ACP(6)=TAHEX/TNMBR(6)
       GO TO 43
    41 TNMBR(6)=0.
       TPEX=TC
       TPF=TA
    43 WK(6)=0.

C       HEAT REQUIREMENT

    56 IF(INPRT.EQ.1)PRTHT=TF2*3600.*CF*(TMPPR-TPF)
       HGAS=DGP*(TC-TA)*0.0723
       HEVAP=H2OEV*(1025.+0.805*(TC-TA))
       HEFF=TF4*CF*(TPEX-TA)*3600.
       HRXN=DGP*61.6
       HLOSS=(ACP(5)**(2./3.))*TNMBR(5)*(TC-TA)*96.63
       HREQ=HGAS+HEVAP+HEFF+HLOSS-HRXN       +PRTHT*0.1
       IF(INDIG.EQ.1)HREQ=HGAS+HEVAP+HLOSS-HRXN
       IF(HREQ.LE.0.)HREQ=0.
       TBVS4=TBVS3*(1.-FCONV)
       TVS4=TVS3-(TBVS3-TBVS4)
       TW4=TW3-H2OEV/2000.
       TS4=TF4-TW4
       TA4=TS4-TVS4

C       DEWATERING

       IF(INDWT)71,71,72
    72 NDWT=TF4/(DWTMC*24.)
       TNMBR(7)=1.+NDWT
       ACP(7)=TF4/(24.*TNMBR(7))
       WK(7)=TNMBR(7)*ACP(7)*DWTWK
       TS5=TS4*FDWT
       TW5=TS5/FS5*(1.-FS5)
       TF5=TS5+TW5
       GO TO 73
    71 TNMBR(7)=0.
       WK(7)=0.
       TS5=0.
       TW5=0.
       TF5=0.
    73 TS6=TS4-TS5
       TF6=TF4-TF5
       TW6=TW4-TW5
```

```
C       GAS PURIFICATION
```

```
      IF(INGPU)81,81,82
  82  ACP(8)=DGP/0.6
      TNMBR(8)=1.
      WK(8)=ACP(8)*GPUWK/1.E6
      GO TO 88
  81  TNMBR(8)=0.
      WK(8)=0.
  88  CONTINUE
      DGPM=DGP/1000.
      HREQM=HREQ/1.E6
      WRITE(6,1001)FO,FSF,FVSF,FBVSF
      IF(INSTP)701,701,702
 701  WRITE(6,1501)
      GO TO 803
 702  WRITE(6,1502)TNMBR(1),ACP(1)
 803  IF(INSHR)800,800,801
 800  WRITE(6,1002)
      GO TO 805
 801  WRITE(6,1003)TNMBR(2),ACP(2),WK(2)
 805  IF(INHLD)820,821,822
 820  WRITE(6,1008)
      GO TO 829
 821  WRITE(6,1009)
      GO TO 825
 822  WRITE(6,1010)
 825  WRITE(6,1011)TNMBR(3),ACP(3),WK(3)
 829  IF(INPRT)810,810,811
 810  WRITE(6,1006)
      GO TO 815
 811  WRITE(6,1007)CHEM,EPRT,TNMBR(4),ACP(4),TCHEM,WK(4)
 815  WRITE(6,1012)
      IF(INDIG)831,833,838
 831  WRITE(6,1013)
      GO TO 835
 833  WRITE(6,1014)
      GO TO 835
 838  WRITE(6,1015)
 835  WRITE(6,1016)TNMBR(5),ACP(5),TC,HRTDG,FCONV,WK(5),GPD,DGPM
      IF(INHEX)841,841,842
 842  WRITE(6,1017)TNMBR(6),ACP(6)
 841  WRITE(6,1018)HREQM
      IF(INDWT)850,850,851
 850  WRITE(6,1019)
      GO TO 852
 851  WRITE(6,1020)TNMBR(7),ACP(7),WK(7)
 852  IF(INGPU)860,860,861
 860  WRITE(6,1021)
      GO TO 862
 861  WRITE(6,1022)ACP(8)
 862  CONTINUE

C     SYSTEM COSTS

      SUBCS=0.
      DO 100 J=1,KK
      CCOS(J)=CONS(J)*(ACP(J)**EX(J))*OINDX/OIND(J)
```

```
      TCOS(J)=CCOS(J)*TNMBR(J)
  100 SUBCS=SUBCS+TCOS(J)
      TPPMP=SUBCS*PPMP
      SUBCS=SUBCS+TPPMP
      WRITE(6,2000)
      IF(INSTR.LT.1)GO TO 501
      WRITE(6,2004)TCOS(1)
  501 IF(INSHR.LT.1)GO TO 502
      WRITE(6,2001)TCOS(2)
  502 IF(INHLD.LT.0)GO TO 503
      WRITE(6,2002)TCOS(3)
  503 IF(INPRT.LT.1)GO TO 504
      WRITE(6,2003)TCOS(4)
  504 WRITE(6,2005)TCOS(5)
      IF(INHEX.LT.1)GO TO 505
      WRITE(6,2006)TCOS(6)
  505 IF(INDWT.LT.1)GO TO 506
      WRITE(6,2007)TCOS(7)
  506 IF(INGPU.LT.1)GO TO 507
      WRITE(6,2008)TCOS(8)
  507 WRITE(6,2009)TPPMP

C     TOTAL PLANT INVESTMENT
      CSEP=SUBCS*PSEP
      SUB1=SUBCS+CSEP
      CSF=SUB1*PSF
      SUB2=SUB1+CSF
      CCOP=SUB2*PCOP
      CED=SUB2*PED
      SUB3=SUB2+CCOP+CED
      CPC=SUB3*PPC
      SUB4=SUB3+CPC
      CIDC=SUB4*PIDC
      CWC=SUB4*PWC

C     ANNUAL OPERATING COSTS

C     MATERIALS

      TCFS=CPF*TSF*TNDO
      TCCHM=CCHM*TCHEM*TNDO

C     UTILITIES

      TWK=0.
      IF(INDIG.LT.1)GO TO 130
      WK(8)=WK(8)*HPTDG/TNDO
      HREQ=HREQ*HPTDG/TNDO
  130 DO 120 J=1,KK
  120 TWK=TWK+WK(J)
      TCWK=TWK*TNDO*CEP/5.589
      TCST=CST*HREQ*TNDO/EFFS/1.E6

C     LABOR

      TCOL=TMP*AW*WD*365.
      TCML=SUB4*PM
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      TCSV=PSV*(TCOL+TCML)
      TCAH=PAH*(TCOL+TCML+TCSV)

C     SUPPLIES

      TCSO=FOPS*TCOL
      TCMS=TCML

C      LOCAL TAXES PLUS INSURANCE

      TCLTI=PLTI*SUB4
  155 TAGOP=TCFF+TCCHM+TCAH*(1.+1./PAH)+TCSO+TCMS+TCLTI+TCWK+TCST+OCHMC
      TDWCV=CDWV*TS5*TNDO
      TWCV=CEFV*TF6*TNDO*0.24
      TCPNC=TDWCV+TWCV
      TANOP=TAGOP+TCPNC
      CSUP=PSUP*TAGOP
      SUB5=SUB4+CSUP+CIDC+CWC
      RRB=(FDBT*DIR)+(1.-FDBT)*RE
      IF(INDIG.EQ.1)TNDO=HRTDG
      AGP=TVD*GPD*TNDO/1000.
      TACST=TANOP+DEPC*(SUB5-CWC)+0.5*(RRB+FITR/(1.-FITR)*(1.-FDBT)*RE)*
     1(SUB5+CWC)
      UGC=TACST/AGP
      WRITE(6,2020)SUBCS,CSEP,SUB1,CSF,SUB2,CCOP,CEO,SUB3,CPC,SUB4,CIDC,
     2CSUP,CWC,SUB5
      WRITE(6,2050)CRF,TCFF
      IF(INFRT.EQ.1)WRITE(6,2051)CCHM,TCCHM
      IF(INDIG.EQ.1)WRITE(6,2055)UCHMC
      WRITE(6,2052)CEP,TCWK,      CST,TCST,TMP,WO,AW,TCOL,TCML,TCSV,TCAH,
     2TCSO,TCML,TCLTI
  720 WRITE(6,2054)TAGOP,TCPNC,TANOP,TACST,AGP,UGC

      WRITE(6,478)
      ROIM=0.1
      NLIFE=OLIFE
      DEPRC=SUB4/OLIFE
      DO 468 I=1,3
      WORTH=SUB4+CWC+SUB4*ROIM+CSUP*(1.-FITR)
      SUM8=0.
      SUM9=0.
      YR=1.
      DO 470 J=1,20
      DCFF=EXP(-YR*ROIM)
      SUM8=SUM8+DCFF
      SUM9=SUM9+DCFF*((TANOP+DEPRC)*(1.-FITR)-DEPRC)
      IF(NLIFE.LE.J)DEPRC=0.
  470 YR=YR+1.
      DUGC=(WORTH-DCFF*CWC+SUM9)/(SUM8*(1.-FITR)*AGP)
      WRITE(6,479)ROIM,DUGC
  468 ROIM=ROIM+0.05

  478 FORMAT(1H1///15X,*DISCOUNTED CASH FLOW METHOD*/5X,*RETURN ON*,10X,
     1*UNIT GAS COST*/5X,*INVESTMENT*,10X,*($/MM BTU)*/)
  479 FORMAT(7X,F5.2,15X,F7.2)
 1001 FORMAT(1H1///24X,*SYSTEM PERFORMANCE*//1X,*FEED COMPOSITION*//9X,*
     2TOTAL SOLIDS*,24X,F7.1,* TONS/D*                    /9X,*SOLIDS FRACTI
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      3ON IN FEED*,14X,F6.3/9X,*VOLATILE SOLIDS FRACTION IN SOLIDS*,3X,F6
      4.3/9X,*BIODEGR. VOL. SOL. FRACT. IN VOL SOL *,F6.3///)
1002  FORMAT(/1X,*SHREDDING-NONE USED*)
1003  FORMAT(/1X,*SHREDDING*/9X,*NUMBER OF UNITS*,20X,F5.0/9X,*CAPACITY
      2PER UNIT*,13X,                    E10.4,* TONS/HR */9X,*POWER REQUIREM
      3ENT*,20X,E11.4,* HP*)
1006  FORMAT(/1X,*PRETREATMENT-NONE USED*)
1007  FORMAT(/1X,             *PRETREATMENT*/9X,*RATIO OF CHEMICAL TO FEED*,
      213X,F5.3/9X,*CONVERSION EFFICIENCY*,16X,F6.3/9X,*NUMBER OF UNITS*,
      320X,F5.0/9X,*CAPACITY PER UNIT*,13X,                       E10.4,* CU.FT.
      4 */9X,*CHEMICAL REQUIREMENT*,10X,                    E10.4,* TONS/HR */9
      5X,*POWER REQUIREMENT*,20X,E11.4,* HP*)
1008  FORMAT(/1X,*HOLDING-NONE USED*)
1009  FORMAT(/1X,*HOLDING-NO MIXING*)
1010  FORMAT(/1X,*HOLDING-MIXING*)
1011  FORMAT(/9X,*NUMBER OF UNITS*,20X,F5.0/9X,*CAPACITY PER UNIT*,13X,
      2                   E10.4,* CU FT. */9X,*POWER REQUIREMENT*,20X,E11.4,*
      3 HP*)
1012  FORMAT(/1X,*DIGESTION*)
1013  FORMAT(/5X,*CSTR*)
1014  FORMAT(/5X,*PLUG FLOW*)
1015  FORMAT(/5X,*BATCH*)
1016  FORMAT( 9X,*NUMBER OF UNITS*,20X,F5.0/9X,*CAPACITY PER UNIT*,13X,
      2                   E10.4,* CU.FT. */9X,*DIGESTER TEMPERATURE*,16X,
      3F4.0,*C*/9X,*RETENTION TIME*,21X,F6.1,*DAYS*/9X,*CONVERSION EFFICI
      4ENCY*,16X,F6.3/9X,*POWER REQUIREMENT*,20X,
      4E11.4,*HP*//5X,*GAS PRODUCTION*,26X,F7.3,* VVD*/
      541X,E11.4,* MM BTU/D*)
1017  FORMAT( 5X,*HEAT EXCHANGER*/ 9X,*NUMBER OF UNITS*,20X,F5.0/9X,*HEA
      2T EXCHANGER AREA*,10X,                    E11.4,* SQ.FT. *)
1018  FORMAT(/5X,*TOTAL HEAT REQUIREMENT*,12X,E10.4,* MM BTU/D*)
1019  FORMAT(/1X,*DEWATERING-NONE USED*)
1020  FORMAT(/1X,*DEWATERING*      /9X,*NUMBER OF UNITS*,20X,F5.0/9X,*CAP
      2ACITY PER UNIT*,13X,                   E10.4,* TONS/HR */9X,*POWER RE
      3QUIREMENT*,20X,E11.4,* HP*)
1021  FORMAT(/1X,*GAS PURIFICATION-NONE USED*)
1022  FORMAT(1X,*GAS PURIFICATION*//9X,*CAPACITY PER UNIT*,13X,E10.4,
      1* CU.FT./D*)
1501  FORMAT(/1X,*STORAGE - NONE USED*)
1502  FORMAT(/1X,*STORAGE*/9X,*NUMBER OF UNITS*,20X,F5.0/9X,*CAPACITY PE
      1R UNIT*,14X,F9.0,* CU.FT.*)
2000  FORMAT(1H1////,24X,*CAPITAL COST ESTIMATE*//50X,*MAY 1979 COSTS ($
      2)*///5X,*INSTALLED EQUIPMENT*/)
2001  FORMAT(10X,*SHREDDERS*,30X,F20.0)
2002  FORMAT(10X,*HOLDING TANKS*,26X,F20.0)
2003  FORMAT(10X,*PRETREATMENT*,27X,F20.0)
2004  FORMAT(10X,*STORAGE UNITS*,26X,F20.0)
2005  FORMAT(10X,*DIGESTERS*,30X,F20.0)
2006  FORMAT(10X,*HEAT EXCHANGERS*,24X,F20.0)
2007  FORMAT(10X,*DEWATERING UNITS*,23X,F20.0)
2008  FORMAT(10X,*GAS PURIFICATION UNITS*,17X,F20.0)
2009  FORMAT(10X,*MATERIALS HANDLING EQUIPMENT*,11X,F20.0)
2020  FORMAT(49X,*--------------------*/1X, *SUBTOTAL*,40X,F20.0//5X,* S
      2TRUCTURES-ELECT. + PIPING*,17X,F20.0/49X,*--------------------*/1X
      3,*SUBTOTAL*,40X,  F20.0//5X,* SUPPORT FACILITIES*,25X,F20.0/49X,*-
      4-------------------*/1X,*SUBTOTAL CAPITAL INVESTMENT*,21X,F20.0//5
      5X,* CONTRACTOR OVERHEAD + PROFIT*,15X,F20.0//5X,* ENGINEERING + DE
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     6SIGN*,23X,F20.0/49X,*---------------------*/1X, *SUBTOTAL PLANT INV
     6ESTMENT*,23X,F20.0//5X,* PROJECT CONTINGENCY*,24X,F20.0/49X, *----
     7----------------*/1X, *TOTAL PLANT INVESTMENT*,26X,F20.0//5X,* INT
     8EREST DURING CONSTRUCTION*,15X,F20.0//5X,* START-UP COSTS*,29X,F20
     9.0//5X,* WORKING CAPITAL*,28X,F20.0/49X, *---------------------*/1X
     7, *TOTAL CAPITAL REQUIREMENT*,23X,F20.0)
2050 FORMAT(1H1,////,23X,* ANNUAL OPERATING COSTS*//54X,*ANNUAL COST ($
     2)*///5X,* PRODUCTION MATERIALS*//10X,* FEED - $*,              F7.
     32,*/TON*,20X,F20.0)
2051 FORMAT(/10X,* PRETREATMENT CHEMICAL   $*,F7.2,*/TON*, 3X,F20.0)
2052 FORMAT(/5X,* UTILITIES*//10X,* ELECTRIC -* ,F4.1,* CTS./KW-HR*,14X
     2, F20.0//11X,*FUEL  -  $*,                    F5.2,*/MM BTU *,16X,
     3F20.0//6X,*LABOR*//10X,* OPERATING LABOR - MEN PER DAY   *,F4.0/29
     4X,*HRS PER SHIFT  *,F4.1/29X,*HOURLY RATE   $*,F5.2,1X,F20.0//10X,
     5* MAINTENANCE LABOR*,22X,F20.0//10X,* SUPERVISION*,28X,F20.0//5X,*
     8 ADMINISTRATION + OVERHEAD*,19X,F20.0//5X,* SUPPLIES*//10X,* OPERA
     9TING*,30X,F20.0//10X,* MAINTENANCE*,28X,F20.0//5X,* LOCAL TAXES +
     7INSURANCE*,21X,F20.0)
2054 FORMAT(49X,* --------------------*,/2X,*GROSS ANNUAL OPERATING COS
     2T*,21X,F20.0//5X,* CREDITS/PENALTIES COST*,22X,F20.0/49X,* -------
     3-------------*/1X,* NET ANNUAL OPERATING COST*,23X,F20.0//1X,*XXXX
     4XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX*
     5/* XX*,65X,*XX*/* XX*,9X,*TOTAL ANNUAL CAPITAL REQUIREMENT = $*,
     6F12.0,8X,*XX*/* XX*,65X,*XX*/* XX*,9X,*TOTAL ANNUAL GAS PRODUCTION
     7 = *,F10.0,                                   * MM BTU *,8X,*XX*/
     8* XX*,65X,*XX*/* XX*,9X,*UNIT GAS COST = $*,F7.2,
     9                          */MM BTU *,24X,*XX*/* XX*,65X,*XX*/* XXXXXXXXX
     1XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX*)
2055 FORMAT(/10X,* BUFFER CHEMICAL*,24X,F20.0)

  98 CONTINUE
  10 CHEM=CHEM+0.05
  99 CONTINUE
     END
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LIST OF COMPUTER SYMBOLS

A	ft^3 CH$_4$/lb converted
ACP	Equipment size
AGP	Gas production (MM Btu/yr)
AW	Labor cost ($/hr)
BGP	Total gas production, batch process (ft^3)
BLDT	Batch process loading time (days)
CBE	Final bio. vol. sol. conc. (lb/ft^3)
CBI	Initial bio. vol. sol. conc. (lb/ft^3)
CCHM	Cost of pretreatment chemical ($/ton)
CCOP	Cost of contractor's overhead and profit
CCOS	Cost of equipment (per unit)
CDWV	Credit/penalty for dewatered output ($/ton)
CED	Cost of engineering and design
CEFV	Credit/penalty for digester effluent ($/1000 gal)
CEP	Cost of electricity (¢/kwh)
CF	Heat capacity of digester slurry (Btu/lb°F)
CHEM	Amount of pretreatment chemical per solids fed

LIST OF COMPUTER SYMBOLS (Continued)

CIDC	Cost of interest during construction
CONS	Cost constant for equipment
CPC	Cost of project contingency
CRF	Cost of feedstock ($/ton)
CSEP	Cost of electrical and piping equipment
CSF	Cost of support facilities
CST	Cost of steam ($/MM Btu)
CSUP	Startup cost
CWC	Working capital
DCFF	Discounted cash flow factor
DCHMC	Buffer chemical cost
DEPRC	Annual depreciation cost
DGP	Gas production (ft^3/day)
DGPM	Gas production (MM Btu/day)
DIGMC	Digester maximum capacity (ft^3)
DIGWK	Digester work (HP/ft^3)
DIR	Interest on debt
DLIFE	System lifetime (years)
DNSDG	Digester slurry density (lb/ft^3)

LIST OF COMPUTER SYMBOLS (Continued)

DNSHL	Density in holding tank (lb/ft^3)
DNSPR	Density in pretreatment unit (lb/ft^3)
DNSTR	Density in storage (lb/ft^3)
DPRC	Rate of depreciation
DUGC	Unit gas cost, DCF Method ($/MM Btu)
DWTMC	Dewatering maximum capacity (T/hr)
DWTWK	Dewatering work (HP/ton/hr)
EA	Activation energy for Arrhenius rate equation (cal/mole)
EDWT	Efficiency of dewatering
EFFS	Efficiency of steam utilization
ELPRT	Fractional loss in pretreatment
EPRT	Efficiency of pretreatment
EX	Equipment cost scale exponent
FBVSF	Fraction of bio. vol. solids in feed
FBVSM	Fraction of bio. vol. solids in manure
FCONV	Fraction of bio. vol. solids converted to CH_4
FD	Feedstock rate (tons solids/day)
FDBT	Fraction debt
FITR	Federal income tax rate
FMAN	Manure requirement

LIST OF COMPUTER SYMBOLS (Continued)

FSF	Fraction of solids in feed
FSM	Fraction of solids in manure
FS1	Fraction of solids in holding unit
FS2	Fraction of solids in pretreatment
FS3	Fraction of solids in digester feed
FS5	Fraction of solids in dewatered solids stream
FVSF	Fraction of vol. solids in feed
FVSM	Fraction of vol. solids in manure
GPD	Gas production (VVD)
GPUWK	Gas purification work (hp/MM SCFD)
HEFF	Heat content of digester effluent (Btu/day)
HEVAP	Heat content of moisture in gas stream (Btu/day)
HEXMC	Heat exchanger maximum capcity (ft^2)
HGAS	Heat content of gas stream (Btu/day)
HLDMC	Holding/mixing maximum capacity (ft^3)
HLDWK	Holding/mixing work (hp/ft^3)
HLOSS	Heat loss from digester walls (Btu/day)
HREQ	Digester heat requirement (Btu/day)
HREQM	Digester heat requirement (MM Btu/day)

LIST OF COMPUTER SYMBOLS (Continued)

HRTDG	Retention time for digestion (days)
HRTHL	Retention time for holding tanks (days)
HRTPR	Retention time for pretreatment (hrs)
HRTST	Retention time for storage (days)
HRXN	Heat of reaction in digester (Btu/d)
HTC	Heat transfer coefficient in heat exchanger (Btu/hr ft^2°F)
H2OEV	Evaporated water in gas stream (lb/day)
I	Dummy variable
INDIG	Dummy variable for use of digester
INDWT	Dummy variable for use of dewatering
INGPU	Dummy variable for use of gas purification
INHEX	Dummy variable for use of heat exchanger
INHLD	Dummy variable for use of holding tank
INPRT	Dummy variable for use of pretreatment
INSHR	Dummy variable for use of shredder
INSTR	Dummy variable for use of storage
J	Dummy variable
JJ	Dummy variable
K	Dummy variable
KK	Dummy variable

LIST OF COMPUTER SYMBOLS (Continued)

NDIG	Number of digesters
NDWT	Number of dewaterers
NHEX	Number of heat exchangers
NHLD	Number of holding tanks
NLIFE	System life
NPRT	Number of pretreatment units
NSHR	Number of shredders
NSTR	Number of storage units
OIND	Cost index for year of equipment cost estimation
OINDX	Current cost index
PAH	Fraction of labor cost for administration and overhead
PCOP	Fraction of equipment cost for contractor's overhead and profit
PED	Fraction of equipment cost for engineering and design
PIDC	Fraction of total plant investment for interest during construction
PLTI	Fraction of total plant investment for local taxes and insurance
PM	Fraction of total plant investment for maintenance labor
--	Fraction of total plant investment for maintenance supplies
POPS	Fraction of operating labor cost for operating supplies
PPC	Fraction of subtotal plant investment for project contingency

LIST OF COMPUTER SYMBOLS (Continued)

PPMP	Fraction of equipment cost for materials handling equipment
PRTHT	Pretreatment heat requirement (Btu/day)
PRTMC	Pretreatment maximum capacity (ft^3)
PRTWK	Pretreatment work (hp/ft^3)
PSEP	Fraction of equipment cost for electricity and piping
PSF	Fraction of equipment cost for support facility
PSUP	Fraction of annual gross operating cost for plant start-up
PSV	Fraction of labor cost for supervision
PWC	Fraction of total plant investment for working capital
RE	Return on equity
RK	Rate constant (day^{-1})
RKO	Rate equation constant (day^{-1})
ROIM	DCF return on investment
RRB	Return on rate base
SHRMC	Shredder maximum capacity
SHRWK	Shredder work (HP/tons/hr)
STF	Stream factor (fraction of year in operation)
STRMC	Storage maximum capacity (ft^3)

LIST OF COMPUTER SYMBOLS (Continued)

SUBCS	Subtotal equipment cost
SUB1	Total equipment cost
SUB2	Cost subtotal
SUB3	Subtotal plant investment
SUB4	Total plant investment
SUB5	Total capital requirement
SUM8	Sum used in DCF calculation
SUM9	Sum used in DCF calculation
TA	Ambient temperature (°C)
TACST	Annual capital requirement
TAF	Total ash in feed (tons/day)
TAGOP	Annual gross operating cost
TAHEX	Total required heat exchanger area (ft^2)
TANOP	Annual net operating cost
TA2	Total ash leaving pretreatment (tons/day)
TA3	Total ash entering digester (tons/day)
TA4	Total ash leaving digester (tons/day)
TBVSF	Total bio. vol. solids in feed (tons/day)
TBVS2	Total bio. vol. solids leaving pretreatment (tons/day)
TBVS3	Total bio. vol. solids entering digester (tons/day)
TBVS4	Total bio. vol. solids leaving digester (tons/day)

LIST OF COMPUTER SYMBOLS (Continued)

TC	Digester temperature (°C)
TCAH	Annual cost for administration and overhead
TCCHM	Annual cost for pretreatment chemicals
TCFF	Annual cost for feedstock
TCHEM	Pretreatment chemical requirement (ton/hr)
TCLTI	Annual cost for local taxes and insurance
TCML	Annual cost for maintenance labor
TCMS	Annual cost for maintenance supplies
TCOL	Annual cost for operating labor
TCOS	Total equipment cost for each process step
TCPNC	Annual credit/penalty cost
TCSO	Annual cost for operating supplies
TCST	Annual cost for steam
TCSV	Annual cost for supervision
TCWK	Annual cost for electricity
TDWCV	Annual credit/penalty for dewatered solids
TFF	Total feed stream (tons/day)
TF1	Total flow from holding tank (tons/day)

LIST OF COMPUTER SYMBOLS (Continued)

TF2	Total flow from pretreatment (tons/day)
TF3	Total flow to digester (tons/day)
TF4	Total flow from digester (tons/day)
TF5	Total flow from dewatering, high solids stream (tons/day)
TF6	Total flow from dewatering, low solids stream (tons/day)
TGBVS	Total gain in biodegradable volatile solids in pretreatment (tons/day)
TLBVS	Total loss in biodegradable volatile solids in pretreatment (tons/day)
TMP	Manpower requirement
TMPPR	Pretreatment temperature
TMS	Total manure solids (tons/day)
TMW	Total manure water (tons/day)
TNDO	Number of days of operation per year
TNMBR	Number of units per processing step
TPEX	Temperature of digester effluent leaving heat exchanger (°C)
TPF	Temperature of influent stream leaving heat exchanger (°C)
TPPMP	Annual cost for materials handling equipment
TSF	Solids in feedstock (tons/day)
TS2	Solids leaving pretreatment (tons/day)
TS3	Solids entering digester (tons/day)

LIST OF COMPUTER SYMBOLS (Continued)

TS4	Solids leaving digester (tons/day)
TS5	Solids leaving dewaterer, high solids stream (tons/day)
TS6	Solids leaving dewaterer, low solids stream (tons/day)
TVD	Total digester volume (ft^3)
TVSF	Vol. solids in feed (tons/day)
TVS2	Vol. solids leaving pretreatment (tons/day)
TVS3	Vol. solids entering digester (tons/day)
TVS4	Vol. solids leaving digester (tons/day)
TWCV	Annual credit/penalty for dewatered low solids stream
TWF	Water content in feedstock (tons/day)
TWK	Total horsepower
TW1	Water leaving holding tank (tons/day)
TW2	Water leaving pretreatment (tons/day)
TW3	Water entering digester (tons/day)
TW4	Water leaving digester (tons/day)
TW5	Water leaving dewaterer, high solids stream (tons/day)
TW6	Water leaving dewaterer, low solids stream (tons/day)
UGC	Utility financing method unit gas cost ($/MM Btu)

LIST OF COMPUTER SYMBOLS (Continued)

WD	Hours per work day
WDIG	Water requirement for digesters (tons/day)
WH	Water requirement for holding unit (tons/day)
WK	Work process step (HP)
WORTH	DCF first year cash flow
WP	Water requirement for pretreatment (tons/day)
XX	Mole fraction of water in digester gas stream
YR	Cash flow year in DCF method

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16. Abstract (Limit: 200 words)

This study provides cost estimates for the pretreatment/digestion of crop residues to fuel gas. Agricultural statistics indicate that the crop residues wheat straw, corn stover, and rice straw are available in sufficient quantity to provide meaningful supplies of gas. Engineering economic analyses were performed for digestion of wheat straw, corn stover, and rice straw for small farm, cooperative, and industrial scales. The results of the analyses indicate that the production of fuel gas from these residues is, at best, economically marginal, unless a credit can be obtained for digester effluent. The use of pretreatment can double the fuel gas output but will not be economically justifiable unless low chemical requirements or low-cost chemicals can be utilized. Use of low-cost "hole-in-the-ground" batch digestion results in improved economics for the small farm size digestion system, but not for the cooperative and industrial size systems. Recommendations arising from this study are continued development of autohydrolysis and chemical pretreatment of agricultural crop residues to improve fuel gas yields in an economically feasible manner; development of a low-cost controlled landfill batch digestion process for small farm applications; and determination of crop residue digestion by-product values for fertilizer and refeed.

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