Cornell University
College of Agriculture and Life Sciences
A Statutory College of the State University of New York
Ithaca, New York 14853

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ANAEROBIC FERMENTATION OF AGRICULTURAL RESIDUES--
POTENTIAL FOR IMPROVEMENT AND IMPLEMENTATION

Twelfth Quarter Progress Report for Period From
March 16, 1979 to June 15, 1979

Plus

Addendum Describing Project Activities From
June 16, 1979 to October 15, 1979

MASTER

Principal Investigator

W.J. Jewell, Associate Professor
Department of Agricultural Engineering
202 Riley Robb Hall
Cornell University
Ithaca, New York 14853

Full-Time Researchers

S. Dell'Orto, K. Fanfoni, T.D. Hayes
J. Chandler

Graduate Students

J.W. Morris

Cooperators

R.W. Guest, D.R. Price, W.W. Gunkel, P.J. Van Soest

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ANAEROBIC FERMENTATION OF AGRICULTURAL RESIDUES--
POTENTIAL FOR IMPROVEMENT AND IMPLEMENTATION

SUMMARY

The Cornell University project on the conversion of agricultural residues to biogas has as its goal the development of a low-cost methane gas generation system for use on small agricultural operations. This progress report covers the activities included in the last scheduled quarter of this study. Due to the delay of funding in the early phase of this study, however, it will be necessary to finish testing and report preparation during the summer and fall of 1979.

Five different types of anaerobic fermentor reactor designs were operated, with the majority of effort focussed on two full scale reactors (both about 35m³), each designed to process the manure residues from up to 65 dairy cows. Three pilot units (5m³ volume) are being operated to determine the limits of operation variables--temperature, labor inputs, mixing, and bedding composition. Variables being evaluated with the pilot reactors include: temperature of operation (25°C and 35°C), straw and sawdust bedding addition, intermittent feeding (once per day to once per week), mixing (none to once per 4 days), and moisture content (90 percent to 60 percent moisture).

The low-cost full scale plug flow reactor has now been operated for more than one year, including the winter with the lowest temperature (down to minus 25°C) for the longest period recorded for the northern New York area. During the twelfth quarter the full scale plug flow and conventional control reactors were tested in parallel at new conditions of 15 days and 10 days HRT, 35°C and 10-12% TS manure feed. Steady state results for the 15 day HRT condition once more indicated a more efficient solids conversion with the plug flow design (34.1 percent TVS destruction efficiency) than with the completely mixed full scale system (27.8 percent TVS destruction efficiency) when operated on dairy manure (13% TS) at 35°C. No serious operational problems have been encountered with either full scale reactor during the twelfth quarter.

Thermal data from the plug flow reactor has now been obtained for a full year cycle. The apparent overall efficiency of the boiler and reactor heating systems varied between 40 and 55 percent. In order to translate the temperature and operating data of the plug flow unit into a comprehensible energy balance, a computer model for the prediction of energy production and for the description of conducted heat losses and feed heating requirements was developed. The computer program was written in BASIC and used on a Hewlett Packard desk top calculator, model 9830.

Data analysis and the development of certain sections of the final report were given considerable attention throughout the twelfth quarter. Writing on the preparation of the farmer's feasibility manual was also initiated during this period.

Activities throughout the coming summer months will include continued operation of the full scale fermentors through conditions of 10 days HRT at 35°C and 30 days HRT at a reduced temperature, 25°C. It is anticipated that the completion of the last scheduled test runs and preparation of the final report will extend into the 13th quarter (summer, 1979).

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Anaerobic Fermentation of Agricultural Residues---

Potential for Improvement and Implementation

INTRODUCTION

It is virtually undebatable that the continued heavy dependence of the U.S. on foreign oil has the potential of seriously aggravating a multitude of world-wide issues related to inflation, unemployment, poverty, political unrest, currency devaluation, recession, foreign policy, etc. However, the severe social and political effects of rapidly increasing energy prices may be mild compared to the potential disruptions that could occur with only modest cutbacks in Middle East oil production. There is definitely an urgent need for accelerated programs of energy conservation and alternative energy development. As new sources of energy are sought, fuels from biomass should receive increased emphasis since the potential of generating a significant amount of clean, renewable fuel from photosynthetically fixed solar energy appears to be economically and technically feasible in many instances.

This is the twelfth quarter progress report describing the activities of an ongoing three-year research effort to facilitate the development of new and/or improved technology that will result in the widespread implementation of anaerobic fermentation as a source of renewable energy for small-scale agriculture. This report describes the progress of events in the last three months contributing to the continued demonstration of low-cost, simplified reactor concepts at the pilot and full scale levels in the conversion of dairy farm manure residues to methane.

The methane project is now obtaining data from simplified pilot

and full-scale fermentors operated on dairy cow manure. The following reactor types have been constructed and operated:

1. Pilot scale randomly fed and mixed, three-cow residue handling capacity when operated at a 30-day HRT;
2. Pilot scale plug flow reactor, three-cow residue handling capacity when operated at a 30-day HRT;
3. Pilot scale semi-solid reactor operating with wheat straw and dairy manure.
4. Full-scale plug flow reactor, 65-cow residue handling capacity when operated at a 10-day HRT; and
5. Full-scale conventional completely mixed control, same residue handling capacity as the full-scale plug flow fermentor.

The overall progress attained with the main phases of the project is estimated to be about 3 months behind schedule, and 5 months behind the original proposed starting date of June 1, 1976. An accelerated experimental program planned for the next quarter should bring the tasks up to the time schedule as proposed, with only a few tasks remaining variables to be tested during the summer of 1979.

Activities for the twelfth quarter, extending from March 16, 1979, to June 15, 1979, have included the following:

1. Collection of steady state data from the full scale plug flow reactor and control unit operated at 15 days HRT, 35°C and 10-12% TS manure feed.
2. Initiation of the full scale reactors into the next condition of 10 days HRT at 35°C and 10-12% TS manure feed.
3. Completion of the last run of the pilot scale plug flow fermentor with steady state data collecting at 25°C, 30 days HRT and 11-13% TS straw and manure feed.
4. Completion of the final experiment with the pilot scale random mix reactor operated at 25°C, 28 days HRT, fed every 7 days with 11-13% manure and straw.
5. Termination of both pilot units and storage of these two units for possible future use.
6. Continued operation of the pilot scale semisolid reactor.

7. Preparation and use of a computer model to predict energy balances for the Cornell plug flow digester and plug flow digesters of varied capacity operated on dairy cow manure.
8. Analysis of data collected from the demonstration phase of the project, from June 15, 1977 to present.
9. The beginning of preparation of the final report of the methane project.
10. The initiation of writing on the Farmer's Feasibility Manual.

OBJECTIVES

The general approach of this new phase of the project will be to define unique approaches to methane generation that will result in economical methane alternatives for small scale agriculture. Specific objectives of this study will be to:

1. Develop the basis for minimal acceptable cost and management required for small-scale fermentor development;
2. Demonstrate cost-effective designs and manageable technology for typical farming operations using the dairy as an example at the 65-head herd size (about 0.5 tons dry matter feed rate per day);
3. Define lower limits for major parameter specification for successful fermentor operation in terms of mixing, insulation, temperature, feed rate, and management requirements in a cold climate with full-size fermentors;
4. Review alternative construction materials useful for decreased capital cost of fermentor construction and operation; and
5. Develop a practical feasibility manual for small scale fermentor design, construction, and operations, using the study results.

PROJECT STATUS

Proposed Status

The work plan originally submitted with the proposal is presented in Figure 1. A bar chart schedule indicating the proposed and actual progress of certain project components is presented in Figure 2. During the twelfth quarter, the pilot and full scale fermentors were to complete their scheduled tests, the pilot reactors were to be terminated and full scale reactors were to be maintained for possible future studies. The pilot scale random mix reactor (5.0 m^3) was to conclude its experimental testing with manure and bedding at low temperatures and close its operation. The pilot scale plug flow reactor (5.6 m^3) was to continue its operation on the manure and bedding feedstock. Also scheduled for the twelfth quarter was the collection of steady state data from the last operating conditions of the full scale plug flow and conventional control reactor (34 m^3) which included testing at 10 days HRT, 35°C with 10-12% manure feed and testing at a reduced temperature (25°C) at 30 days HRT.

Present Status

Long-term operation of the full scale low-cost reactor has now been ongoing continuously for more than a year. Successful operation of this design has provided a basis for suggesting that small scale methane generation may be technically and economically feasible, thus providing positive information on the main goal of this study.

The overall progress is presently about three months behind the proposed schedule. Experimentation with the pilot scale reactors has been completed in accordance with the work plan. However, the full scale demonstration phase has had delays, mainly due to the adversity

Figure 1. Detailed work plan for the development and demonstration of low cost fermentors.

FIGURE 2. CORNELL UNIVERSITY METHANE PROJECT WORK PLAN

* Substituted with a manure feed experiment at 35°C, 15 days HRT on the basis of observation from bedding addition tests conducted on the pilot scale plug flow fermentor. See Figure 3 comment.

of severe winter weather during the initial construction phase (December 1977 - March 1978). The revised experimental plan was drafted to accelerate the testing program and to narrow the schedule gap, as shown in Figure 3. Progress in reference to the new schedule is indicated, showing a 2 1/2 month overall delay behind the accelerated work plan.

It should be pointed out that as soon as the time for testing the reactors on bedding (as per the work plans of Figures 1 and 2) was reached, a decision had to be made concerning the advisability of straw addition to the large scale units in light of past experience with the pilot scale plug flow reactor. As mentioned in previous progress reports, the addition of straw bedding to the influent of the pilot scale plug flow system while operating under conditions of 15 days HRT, 35°C and 30 days HRT, 25°C, had the pronounced effect of an accumulation of a straw float layer which grew to a substantial thickness, 8-12 inches within two months of operation. Hence, it was decided that the pilot-scale experience was sufficient to predict the probable result of adding certain bedding materials (straw and wood chips) to the influent feed of an unmixed plug flow reactor. It was reasoned that other operating conditions on manure at 35°C and at a low temperature (25°C) would be more useful than the potentially debilitating straw bedding experiments originally planned. These substitutions of experimental protocol are indicated on Figure 3.

Pilot Scale Random Mix Reactor

During the twelfth quarter, the final experiment with the 5.0 m³ pilot scale random mix reactor was completed and the operation of this

Figure 3. EXPERIMENTAL TESTING PROGRAM

Twelfth Quarter
Progress Report

PILOT SCALE

Plug	28°C 30d	25°C 15d	35°C 30d HRT	35°C 15d HRT	25°C 30d HRT
Flow	Manure		Manure + Bedding		

- Temperature
- Hydraulic Retention Time, days
- Feed Type - in all cases the concentration of manure feed will range 10-12% TS and the manure-bedding mixture will range 11-13% TS.

Random
Mix

35°C 30d	35°C 30d: 1/week feed	35°C 15d: 2/week feed	28°C 30d
Manure		Manure + Bedding	

FULL SCALE

Plug	Start	35°C 30d	35°C 15d	35°C 10d	25°C 30d
Flow	Manure			Manure*	

Conv.
Control

Start	35°C 30d	35°C 15d	35°C 10d	25°C 30d
Manure			Manure*	

*Since straw bedding additions to the pilot scale plug flow reactor resulted in a substantial accumulation of a straw float layer within a month of operation it was decided that the addition of the same bedding material to the full scale plug flow reactor would have a similar disruptive effect. Consequently, it was decided that an additional test run at 35°C 10 days HRT would be more useful than the potentially debilitating bedding addition experiment.

unit was terminated. This reactor was designed to handle manure from 3 to 10 cows when operated at hydraulic retention time (HRT) between 30 and 10 days. Throughout the twelfth quarter this unit was operated on a bedding and manure feed mixture at a reduced temperature of 25°C, and fed one quarter of the reactor's volume every seven (7) days; at this feeding mode the reactor was operated at a 28 day HRT. The contents of this limited-mix reactor were only recirculated for a brief period following every feeding. In this last experiment, straw was added to the influent manure on the basis of a bedding utilization rate of 0.93 kg/cow/day (2.0 lbs/cow/day).

At this operating mode the random mix reactor produced biogas at an average rate of about $1.12 \text{ m}^3/\text{m}^3$ reactor-day ($0.69 \text{ m}^3/\text{m}^3$ reactor-day of methane) with a concomitant total volatile solids (TVS) destruction of 26.9 percent. Steady state data from this latest operating condition are shown in Table 1. No significant accumulations of straw bedding, either as a float or settled solids, were observed during the manure-straw feed condition at 25°C for the random mix system.

Comparisons of reactor performances at this condition with data from other operating modes are also provided in Table 1. It is particularly interesting to note that at a 28 day HRT (feeding and mixing every 7 days) the random mix reactor yielded nearly as much daily methane when fed 11-13% TS manure and straw at 25°C ($0.69 \text{ m}^3/\text{m}^3$ reactor-day) as it did when fed 10-12% TS manure with no bedding at 35°C ($0.74 \text{ m}^3/\text{m}^3$ reactor-day).

Upon completion of the bedding addition experiment at 25°C, the

TABLE 1. PERFORMANCE DATA FOR THE RANDOM MIX REACTOR OPERATED AT 35°C

Operational and Performance Parameters	Operating Conditions				
	10-12% TS Manure 30 days HRT	10-12% TS Manure 28 days HRT	10-12% TS Manure 16 days HRT	11-13% TS Manure & Straw 16 days HRT	11-13% TS Manure & Straw 28 days HRT
Feeding Frequency	once/day	once/7 days	once/4 days	once/4 days	once/7 days
Mixing Frequency	once/10 days	once/7 days	once/4 days	once/4 days	once/7 days
Days of Operation	104	90	52	70	55
Average Gas Production					
m^3/day	10.1	6.4	8.2	10.0	6.0
$\text{m}^3/\text{m}^3 \text{ reactor/day}$	2.0	1.3	1.6	2.0	1.12
Methane Production					
m^3/day	6.3	3.7	4.9	5.9	3.7
$\text{m}^3/\text{m}^3 \text{ reactor/day}$	1.3	0.74	0.98	1.2	0.69
Effluent pH	7.8	7.7	7.6	7.7	7.7
TVS Destruction, Percent	37.0	31.4	28.7	22.3	24.5

random mixed reactor was discontinued in operation. The contents of this unit were pumped out and the system was placed in storage for possible dismantling in future months. Random mix reactor experimentation was completed nearly as scheduled.

Pilot Scale Plug Flow Fermentor

The pilot scale plug flow fermentor (5.6 m^3) completed its last experimental run during the twelfth quarter while operated on a feed mixture of manure and bedding. Throughout this period, this reactor system was operated at a mode of 11-13% TS influent, 30 days HRT and 25°C . Bedding was added to the feed at a blending rate equivalent to about 0.68 kg/cow/day (1.5 lbs/cow/day). At this operating condition, the pilot plug flow reactor was producing biogas at a steady rate of about 4.7 m^3 per day ($0.84 \text{ m}^3/\text{m}^3$ reactor/day) with a total volatile solids destruction efficiency of 18.0 percent. Steady state data obtained from this condition with bedding addition at 25°C are tabulated in Table 2; data from other previous operating conditions when bedding materials were added to the feed are also included in Table 2.

As mentioned in previous progress reports, the behavior of bedding materials when introduced into the plug flow fermentor with respect to separation from manure seemed to depend upon the type of bedding used and the operating temperature of the digester. Wood chips introduced into the feed at the 30-day HRT, 35°C operating condition did not result in separation while straw introduced at this mode and at a 15-day HRT, 35°C condition produced a fibrous float of 0.15 m (6.0 inches) to 0.76 m (30 inches) thick inside the reactor basin within two months of operation. On the other hand, operation at a reduced temperature of

TABLE 2. SUMMARY OF PERFORMANCE DATA FOR THE PILOT SCALE PLUG FLOW FERMENTOR OPERATED ON DAIRY MANURE AND BEDDING FEEDSTOCKS, 35°C, 11-13% TS FEED.

Performance Parameter	30 days HRT Wood Chips* 35°C	30 days HRT Chopped Straw** 35°C	15 days HRT Chopped Straw** 35°C	30 days Straw 25°C
Days of Operation	44	89	32	55
Influent Solids g/l TS	123	119	118	127
Effluent Solids g/l TS	91.9	81.3	92.2	107.2
Solids Destruction				
TS %	25.5	31.5	21.7	20.1
TVS %	28.9	35.2	25.1	18.0
Effluent pH	7.5	7.5	7.8	7.7
Effluent Alkalinity g/l	16.8	13.6	19.6	19.7
Gas Production				
m ³ /day	5.50	4.67	5.85	4.67
m ³ /m ³ reactor/day	0.98	0.84	1.05	0.84
Methane Production				
m ³ /day	3.30	2.61	3.39	2.76
m ³ /m ³ reactor/day	0.59	0.47	0.61	0.50
m ³ CH ₄ /Kg VS _D	0.55	0.38	0.35	0.73
Gas Composition (Percent CH ₄)	60	56	58	59

* Data from the tenth quarter period.

** Data from the eleventh quarter period.

25°C at 30 days HRT allowed prolonged fermentation without straw/manure separation. Apparently, the increased viscosities produced at 25°C in 11-12% TS dairy manure are sufficient to prevent the upward movement of straw fibers caused by gas bubble attachment.

A comparison of straw bedding experiments at 30 days HRT reveals that the methane gas production at 25°C ($0.50 \text{ m}^3/\text{m}^3 \text{ reactor/day}$) was approximately equal to the methane production at 35°C ($0.47 \text{ m}^3/\text{m}^3 \text{ reactor/day}$). The expectation here, however, would be that far higher energy production should be achievable at the 35°C condition. It seems evident that straw fiber accumulations in the 35°C experiment severely reduced the effective reactor volume to the extent where gas production performance was significantly hindered. It is estimated that, at 35°C, straw fiber had occupied as much as 30 to 40 percent of the reactor; hence, the HRT of the system was effectively reduced from 30 days to about 21 days and the actual conversion efficiencies of organics to methane were substantially decreased from about 0.55 to as low as $0.38 \text{ m}^3 \text{ CH}_4/\text{kg}$ volatile solids destroyed.

Experimentation on the pilot scale plug flow reactor was concluded with the collection of steady state data from the final bedding-addition condition at 25°C. All operating conditions outlined for this unit in the work plan have been tested and the pilot study on plug flow fermentation was ended close to the proposed schedule.

Full Scale Plug Flow Fermentor and Completely Mixed Control Unit

Two operating conditions were applied to the full scale plug flow and conventional control fermentors during the twelfth quarter:

15 days and 10 days HRT at 35°C while fed about 13 percent TS dairy manure. For reasons previously given, bedding was not added to the feedstock of the full scale reactors. The experiment at 15 days HRT was completed about two months into the twelfth quarter; steady state data obtained from this condition is shown in Table 3.

Upon completion of the 15-day condition, the hydraulic retention time of the full scale units was then reduced to 10 days HRT. Some initial steady state data for this unit are given in Table 4.

For comparison purposes, the solids destruction and gas production performances of the full scale units operated at 10, 15 and 30 days HRT (35°C, 13% TS manure feed) are tabulated in Table 5; plots of solids conversion and methane yield are presented in Figure 4. The data for the full scale systems indicate that the plug flow reactor consistently maintained higher rates of solids conversion to biogas than its full scale completely mix control. The newest information from the full scale demonstration study agrees well with the results from bench and pilot reactor studies and strongly suggests that the anaerobic fermentation of manure can be greatly simplified in design, operation and cost without sacrificing performance in converting organics to biogas.

By the end of the twelfth quarter period the 10-day HRT condition was nearly completed. By the end of the twelfth quarter, the full scale demonstration effort was running about three months behind the revised schedule.

Plug Flow Fermentor Energy Balance Computer Model

One of the most important aspects of the design and construction of simplified, earthen fermentors is the careful usage of soil drainage

TABLE 3. STEADY STATE DATA FROM THE OPERATION OF THE FULL SCALE PLUG FLOW AND CONVENTIONAL CONTROL FERMENTORS AT 10 DAYS HRT, 35°C and 10-12% TOTAL SOLIDS DAIRY MANURE FEED.

	Completely Mixed Reactor	Plug Flow Reactor
Condition, HRT, days	9.8	10.4
Feed Rate, m ³ /day	3.65	3.80
Days of Operation	38	38
Days of Steady State	18	18
Total Solids, gm/l		
Infl.	125.8	125.8
Effl.	96.9	92.4
Red.		
Red., %	23.0	26.6
Total Volatile Solids, gm/l		
Infl.	110.0	110.0
Effl.	81.2	76.8
Red.	28.8	33.2
Red., %	26.2	30.2
Total Biod. Volatile Solids, gm/l		
Refr. Fraction	0.56	0.56
Refr. Solids	61.6	61.6
Infl.	48.4	48.4
Effl.	19.6	15.2
Red.	28.8	33.2
Red., %	59.5	68.6
Gas Production, STP		
m ³ /day	82.4	97.3
% CH ₄	60	60
m ³ CH ₄ /day	49.5	58.4
Ft ³ CH ₄ /day Predicted from BVS dest.	52.6	63.1
Ratio (predicted/observed)	1.06	1.08

TABLE 4. STEADY STATE DATA FROM THE OPERATION OF THE FULL SCALE PLUG FLOW AND CONVENTIONAL CONTROL FERMENTORS AT 15 DAYS HRT, 35°C AND 10-12 PERCENT TOTAL SOLIDS DAIRY MANURE FEED

	Completely Mixed Reactor	Plug Flow Reactor
Condition, HRT, days	14.8	16.1
Feed Rate, m ³ /day	2.39	2.45
Days of Operation	57	107
Days of Steady State	26	23
Total Solids, gm/l		
Infl.	129.1	129.1
Effl.	97.9	91.0
Red.	31.2	39.1
Red., %	24.2	29.5
TVS, gm/l		
Infl.	112.1	112.1
Effl.	80.9	73.9
Red.	31.2	38.2
Red., %	27.8	34.1
TBVS, gm/l		
Refr. Fraction	0.56	0.56
Refr. Solids	62.7	62.7
Infl.	49.4	49.4
Effl.	18.2	11.2
Red.	31.2	38.2
Red., %	61.1	75.3
Gas Production STP		
m ³ /day	75.3	92.5
% CH ₄	55	55
m ³ CH ₄ /day	41.4	50.9
m ³ /CH ₄ /day predicted from	37.3	46.8
BVS Destruction (ratio of		
predicted/observed)	0.90	0.92

TABLE 5. SUMMARY OF FULL SCALE OPERATION OF DAIRY MANURE ANAEROBIC FERMENTORS WHEN FED A TS FEED OF 129 gm/l.

		10-day HRT	15-day HRT	30-day HRT	
Gas Production	vol/vol	2.33	2.13	1.13	FULL SCALE COMPLETELY MIXED REACTOR (1250 ft ³)
	l/gm VS _A	0.205	0.281	0.310	
	ft ³ /lb VS _A	3.3	4.5	5.0	
Gas Composition	% CH ₄	60	55	58	
Solids Destruction	% TVS red	26.2	27.8	31.7	
	% TBVS red	59.5	61.9	70.4	
Gas Production	vol/vol	2.52	2.33	1.26	FULL SCALE PLUG FLOW REACTOR (1360 ft ³)
	l/gm VS _A	.233	0.337	0.364	
	ft ³ /lb VS _A	3.7	5.4	5.8	
Gas Composition	% CH ₄	60	55	57	
Solids Destruction	% TVS red	30.2	34.1	40.6	
	% TBVS red	68.6	75.8	90.1

Figure 4. Comparison of solid conversion efficiency in full scale completely mixed and plug flow reactors fed about 13 percent solids dairy manure.

and insulation to conserve energy that would otherwise be lost through conduction. With the Cornell design, the soil surrounding the reactor was kept as dry as possible with the installation of an extensive under-drain system to reduce the heat conductivity of the ground. The reactor walls were lined with 10.2 cm (4.0 inches) foam glass insulation, the gas collection membrane of the unit was covered with 8.9 cm (3.5 inches) of fiberglass insulation and another impermeable rubber cover was placed over the fiberglass to keep the insulation dry. Finally, all exposed liquid surfaces of the moat and effluent section were covered with a 5.1 cm (2.0 inches) of floating polystyrene.

It is intuitive that adequate insulation for the plug flow digester would be especially important in cold climates. The temperature of northern New York often falls below minus 30°C and can average minus 20°C for several weeks. During this period, the heating demand to maintain an anaerobic fermentor at 35°C will be its highest. The digesters at Cornell are heated with their own biogas; in this case the net biogas available for farm use is equal to the total energy production minus the boiler biogas usage required to maintain reactor temperature. Since the space heating demand on most farms is likely to coincide with a period of low net biogas production, it became evident that a careful analysis of the year-round energy balance of the plug flow methane generator was needed.

In the previous progress report, both of the full scale fermentors at Cornell were characterized with respect to energy balances conducted during the coldest months of an Ithaca winter, January and February. The data clearly showed that uninsulated or poorly-insulated systems could result in a net energy demand instead of a net energy surplus

during critical winter months. During one cold-weather test period, the insulated plug flow reactor at Cornell, sized for handling manure from 32 cows at a 15 day HRT, was able to produce an amount of net energy that was 44 percent of the gross biogas output at an average ambient air temperature of -18°C (one week) and at a reactor temperature of 35°C .

The calculation of an energy balance for the plug flow digester required the daily measurement of gas flows and temperatures. Using two meters it was possible to directly monitor the total biogas produced, biogas utilized by the boiler and the net biogas available for on-farm use. In addition, temperatures of the reactor, the reactor manure feed and the soil surrounding the reactor were taken daily. Average daily and monthly ambient air temperatures were obtained from the Atmospheric and Sciences Department of Cornell University. Gas flow and temperature data accumulated for almost a year have made it possible to calculate the month-by-month energy distributions associated with the Cornell plug flow system. What was needed at this point was a model to extrapolate the energy balance information obtained from the Cornell system to plug flow reactors of varied capacities and designs.

During the twelfth quarter, a computer model was developed, incorporating basic heat transfer relationships and first order kinetic information from Cornell reactors to provide predictions of energy balances for prismoidal plug flow reactors of various shapes, sizes, loading rates and designs. Heat balance components included the conducted heat loss, H_C , the feed heating requirement, H_F , the total biogas produced, H_T , and the net biogas, H_N , available for use. To complete the energy balance, the energy lost due to the overall inefficiency of the boiler and reactor heat exchanger system had to be calculated; the

following equation was used to estimate the overall heating efficiency (E) of the Cornell plug flow digester:

$$E = \frac{100 \times (H_c + H_F)}{H_T - H_N}$$

The value of E was calculated from direct measurements of the total and net gas productions (H_T and H_N , respectively), the feed heating requirement (H_F) as computed from the known influent flow and feed and reactor temperatures, and from the measured conducted heat loss (H_c) obtained by turning off feed and hot water supplies to the digester and recording the reactor temperature drop during a 48-hour period. In the Cornell study, the overall heating efficiency, E, was calculated at around 55 percent. This value was employed in the energy balance model developed for the plug flow reactor, even though greater efficiencies of digester heating could conceivably be achieved through the installation of an automatic stack damper on the gas-fired water heating unit for flue heat conservation and through the use of a water heater instead of a water boiler for greater efficiency of heating recirculated water to temperatures of 60 to 65°C.

Conducted heat losses through the digester top, walls and floor were calculated in the model using the general equation for heat transfer through a flat sheet:

$$H_c = A = 24(T_1 - T_2) \cdot \left[\frac{1}{K_i} + \frac{1}{K_o} + \frac{B_1}{K_1} + \frac{B_2}{K_2} + \dots + \frac{B_n}{K_n} \right]^{-1}$$

where; A = area of section normal to the direction of heat flow (ft²);

T_1 = temperature of the reactor (°F);

T_2 = Temperature outside the digester barrier (soil or air temperature, °F);

K_i, K_o = inside and outside unit surface conductances (Btu/hour-ft²-°F);

K_n = coefficient of thermal conductivity of barrier "n" (Btu-inch/hour-ft²-°F);

and B_n = thickness of barrier "n" (inch).

Feed heating demand was calculated from the straight forward equation:

$$H_F = Q(T_1 - T_2) S = \frac{V(T_1 - T_2)S}{U}$$

where; H_F = feed heating requirement (Btu/day);

Q = feed flow to reactor (ft³/day);

T_1 = temperature of reactor (°F);

T_2 = temperature of feed (°F);

U = hydraulic retention time (days);

V = reactor volume (ft³);

S = density of feed (lbs/ft³).

The total energy production was calculated from a first order kinetic expression developed for solids conversions in plug flow fermentor systems operated between 10 and 30 days HRT. The mass conversion rate of biodegradable volatile solids (BVS) was calculated by the following equations:

$$\text{Influent BVS } S_o = C_o \times (1-R)$$

$$\text{Effluent BVS } S_1 = S_o e^{-ku}$$

$$\text{Biogas Production } H_T = \frac{f(S_o - S_1) Y V 1000}{U} = \frac{1000 f Y V S_o (1 - e^{-ku})}{U}$$

where C_o = influent volatile solids concentration, g/l;

S_o = influent BVS, g/l;

- S_1 = effluent BVS, g/l;
 R = refractory volatile solids fraction = .56;
 f = conversion factor = 0.0623 lbs l/g u ft³;
 k = first order kinetic rate constant, 35°C, for dairy manure, days⁻¹;
 U = hydraulic retention time, days;
 Y = methane yield 8.0 ft³/lb BVS destroyed;
 V = volume of reactor, ft³;
 H_T = total energy production 10⁶ Btu/day.

The components of the energy balance were then used in an energy balance equation to calculate the net energy production of the plug flow digester:

$$H_N = H_T - \frac{100(H_C + H_F)}{E}$$

- where H_N = net energy production, Btu/day;
 H_T = total energy production, Btu/day;
 H_C = conducted heat loss, Btu/day;
 H_F = digester influent heating requirements, Btu/day;
 E = overall digester heating efficiency.

These energy balance equations were incorporated into a model which was written in BASIC program language to be used on a Hewlett Packard desk top computer, model 9830A. The most important input parameters and the ranges of values used for them in the program are tabulated in Table 6. Average monthly temperature data used in this analysis are shown in Table 7; temperatures of the best, base (average) and worse case scenarios are also included. Upon entering the appropriate values for design and operating parameters, an energy balance output on the plug flow

TABLE 6. ASSUMPTIONS AND PARAMETER INPUTS USED FOR THE PLUG FLOW REACTOR ENERGY BALANCE COMPUTER PROGRAM

<u>Parameter</u>	<u>Range of Value(s) Used</u>	<u>Comment</u>
Capacity	25 to 500 dairy cows	
Total Depth	1.5-3.0m (5-10 ft.)	Varies with capacity from 1.5 deep for a 25 cow unit to 3.0 m deep for a 500 cow digester. Shallower digester depths may be advisable for high water table areas.
Liquid Depth	1.04-2.54 m	Total Depth minus 0.46 m freeboard.
Length to Width Ratio as measured at ground surface	3.7	Cornell system L/W ratio.
Slopes of digester walls	45° Endwall 40.6° Sidewall	Walls have to be sloped to 45° or less in order to work with the earthen materials.
Insulation		
Walls	10.2 cm (4")	Foam Glass
Floor	10.2 cm (4")	Foam Glass
Liquid surface, moat and effluent end	5.1 cm (2")	Polystyrene (floating)
Gas collection bag	8.9 cm (3.5")	Fiberglass
Kinetic Information		
First Order Rate Constant, 35°C	0.083 days ⁻¹	Determined from Cornell pilot and full scale plug flow fermentation studies.
Refractory TVS Fraction	0.56	Determined from bench scale batch reactors.

TABLE 7. TEMPERATURE DATA OBTAINED FROM THE CORNELL PLUG FLOW REACTOR AND USED IN THE ENERGY BALANCE MODEL.

Month	T E M P E R A T U R E S, °C				
	Ambient Air	Feed	Effluent	Earthen Wall*	Floor**
Jan	- 7.8	5.0	25.0	14.8	17.8
Feb	-11.1	5.0	25.0	10.0	16.1
Mar	- 2.8	8.0	28.0	13.0	16.1
Apr	5.0	10.0	28.0	14.2	18.3
May	12.2	15.0	29.0	18.0	23.9
June	17.2	18.0	29.0	21.2	26.7
July	19.4	20.0	30.0	19.5	26.7
Aug	19.4	20.0	30.0	19.5	26.7
Sept	13.3	18.0	30.0	20.0	23.9
Oct	7.8	14.0	29.0	20.0	21.1
Nov	3.3	12.0	28.0	17.2	20.0
Dec	- 3.9	7.0	27.0	15.8	19.4
Best Case	19.4	20.0	27.0	19.5	27.0
Worst Case	-11.1	5.0	16.1	10.0	16.1
Average Case	6.0	12.7	19.0	16.9	21.4

* Average of four temperatures taken evenly distributed along the sloping lateral wall 4" into the soil.

** Temperature of soil taken 4" below reactor floor.

fermentor could be obtained as described in Table 8. This program then became a potentially useful tool in translating the data from the 1360 ft³ plug flow reactor operated at Cornell to other hypothetical systems of varied designs, operating conditions and capacities, exposed to different climatic conditions.

Of great interest was the effect of dairy farm size on the net amount of biogas as predicted by the model. This relationship is shown in Figure 5 for a 20-day HRT plug flow fermentor. The computer energy balance model indicated that as the volume of the plug flow reactor is increased the per animal net energy production is generally increased. Reactor scale-up from a 50-cow digester to a 500-cow unit, for example, would likely result in an increase in the normalized net energy production from 23.9 to 27.0 MJ/cow/day, a rise of 12.7 percent.

Greater per cow net biogas yields at the larger reactor capacities are mainly due to the decreased conducted heat loss per unit volume liquid contents; this effect is seen in Figure 6. The high per-volume conducted heat losses, most noticeable at capacities below 100 cows, are predisposed by higher surface area to volume ratios that increase with decreasing reactor capacity for the prismoidal plug flow fermentor design, as shown in Figure 6.

Detailed Energy balances for the computer simulation of 100 and 500 cow reactors operated at 35°C under average case temperature conditions are presented in Table 9. This table shows that the greatest energy demands are exerted by the feed heating requirements and the heating inefficiency of the boiler itself. These demands could be substantially reduced, however, through the addition of automatic stack damping to the water heater to minimize the escape of hot flue gas

TABLE 8. OUTPUT INFORMATION FROM THE CORNELL PLUG FLOW REACTOR ENERGY
BALANCE COMPUTER PROGRAM.

<u>Information Category</u>	<u>Data Printout</u>
I. Reactor Geometry	Length (ft); Width (ft.); Depth (ft.); Endwall Slope (degrees); Sidewall Slope (degrees); Reactor Volume (ft ³).
II. Kinetic Information	HRT (Days); Influent TVS g/l; Refractory Fraction; First Order Rate Constant (Days ⁻¹); Methane Yield (Percent); Energy Production (Btu/day).
III. Energy Balance	
Temperatures (°C)	Reactor; Ambient Air; Influent; Effluent; Biogas; Average Soil 4" from the Reactor Walls;
Energy (Btu/day)	Walls; Floor; Moat Surface; Effluent; Gas Collection Biogas; Total Conducted Heat Loss; Feed Heating; Conducted plus Feed Heating; Water Heater Input, Gross Energy Production; Net Energy Production; Net Energy-percent of Gross Energy Production.

Figure 5. Net Energy Production Per Cow Versus Capacity for Plug Flow Fermentors Operated on Dairy Manure at 35°C in Climates Similar to Upstate New York as Predicted by the Cornell Reactor Energy Balance Model.

Figure 6. Conducted Heat Loss and Wall and Reactor Top Surface Area per Unit Volume Versus Capacity for Plug Flow Fermentors Operated on Dairy Manure at 35°C in Climates Similar to Upstate New York.

TABLE 9. ENERGY BALANCE ON THE PLUG FLOW REACTOR OF 100 AND 500 COW CAPACITIES OPERATED AT 35°C, 20 DAYS HRT, AVERAGE CASE TEMPERATURES.

Energy Component	100 Cows		500 Cows	
	GJ/day**	% of Total	GJ/day	% of Total
Energy Demands				
Walls	0.074	1.9	0.19	1.0
Floor	0.013	0.3	0.059	0.3
Top	0.168	4.4	0.53	2.8
Feed	0.452	11.9	2.26	11.9
Heating Inefficiency	0.578	15.3	2.49	13.1
Net Energy Prod.	2.51	66.2	13.5	70.9
Gross Energy Production	3.80		19.0	

* Assuming an overall reactor heating efficiency of 55%.

** GJ = Giga Joule = 10^9 Joules.

during burner shutdown, and through the use of heat exchange equipment to transfer heat from the effluent at 30°C to the colder influent stream at 2 to 20°C.

The projected year-round variation of net biogas production from a 100 cow plug flow digester operated at 20 days HRT at 35°C, as affected by cold weather, is shown in Figure 7. It would be expected that any energy conservation measures, like those mentioned above, would not only have the effect of increasing the total yearly net energy production, but would tend to buffer the month to month changes in available net energy output as well.

Final Report

Data analysis and the writing of the final report received much attention in the twelfth quarter. A detailed outline of this document was prepared early in the last quarter which will serve as a basis for the general organization of the report. It is expected that the writing of the first draft of the final report will extend well into the summer. By the end of the twelfth quarter period, the preparation of the final report was 1 1/2 months behind schedule.

Feasibility Manual

The initial outline for the feasibility manual has been prepared and will be used as a guide to the format and content of this document. During the twelfth quarter, development of certain sections of the manual was initiated with respect to data and literature collation. This document will not be an extensive or comprehensive set of instructions on the construction of anaerobic fermentation systems, but rather a practical

100 COW DAIRY FARM IN N.Y.S.

Figure 7. Predicted Annual Variation of Net Energy Production from a 100 Cow Plug Flow Anaerobic Fermentor Operated at 20 Days HRT, 35°C, fed 13 percent TS Dairy Manure.

aid to guide farmers through a process of rational decision-making to determine the applicability and economic feasibility of selected low-cost anaerobic fermentation systems to certain farm situations.

Because a great amount of attention was given to completing the pilot reactor experiments, maintaining the full scale reactors and data analysis for the final report, the farmers feasibility manual was not completed in the twelfth quarter. Thus, progress on the preparation of the manual is now behind schedule by about 1 1/2 months.

FUTURE ACTIVITIES

The Cornell Methane Project will continue its work into the summer of 1979, beyond the originally intended concluding date of June 1, 1979. However, as mentioned in previous progress reports, the present demonstration phase of the project fell behind the originally proposed schedule due to an unfortunate 3 1/2 month delay in receiving the necessary funds from DOE. Because the construction of the full scale units was forced to coincide with the winter months, adverse weather added more delays to the start-up and testing of the demonstration scale fermentors. The revised work plan of Figure 3 has helped to accelerate project activities so that the proposed experimentation might be concluded reasonably close to schedule.

Although the pilot-scale reactor testing program has already been concluded, operation of the full scale reactors will be extended into the next three-month quarter period. Within the next two weeks in June, additional steady state data will be obtained from the large plug flow and conventional control reactors while operating at 35°C, 10-12% TS and 30 days HRT. The reactors will then be shifted to low-temperature operation at 25°C while fed dairy manure at 10-12% TS, 30 days HRT.

As previously stated, experimentation at the pilot scale has made it possible to assess the probable response of unmixed plug flow and random mix (intermittant mix) fermentation systems to straw and wood chip bedding additions to dairy manure feeds. Solids accumulation data from the pilot scale plug flow fermentor operated on straw bedding and manure mixtures have shown that straw addition to an unmixed fermentor

at 35°C will probably result in a substantial solids flotation problem, although the same pilot unit at 25°C experienced little problem with float formation. In light of the information already obtained at the pilot scale on bedding-manure feeding, the straw addition runs planned for the full scale units have been replaced with one more manure feed run at 35°C (15 days HRT) and one manure feed condition at 25°C (30 days HRT) to obtain more kinetic information on the full scale fermentation of dairy cow manure.

In the next three months, increased emphasis will be given to the preparation of the final report and the farmers feasibility manual. Data analysis for the next quarter will include continued definition of the full scale and pilot scale simplified reactors and a close examination of the total energy balance on the earthen, full scale, plug flow fermentor under various operating conditions. The development of computer models for fermentor costing and economic analysis will also be a part of the report preparation activities planned for the coming quarter.

Finally, during the next quarter period the Methane Project Team will be prepared to respond to comments or requests for clarification from DOE concerning the continuation proposal submitted to DOE May 18, 1979. The new proposal included a 3-year research plan for areas of continued testing of the dairy farm fermentors (plug flow and conventional control), swine manure fermentation, biogas storage and utilization and dry fermentation of crop residues. Discussions with DOE will continue over the coming months to reach an agreement on the future research directions outlined in the Cornell proposal.

Addendum Progress Report

Anaerobic Fermentation of Agricultural Residues--
Potential for Improvement and Implementation

June 16, 1979 to October 15, 1979

Cornell University
Ithaca, NY

Anaerobic Fermentation of Agricultural Residues--
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PROJECT STATUS

During the period between June 16 and October 15, 1979 the Cornell Methane project continued work toward the completion of the tasks outlined in the work plan. This brief addendum will outline the accomplishments contributing to the progress of the project within this period.

Pilot Scale Plug Flow and Random Mix Fermentor Units

Experiments involving these reactors were concluded in the twelfth quarter period. During the summer months these systems were cleaned out partially dismantled. Some of the components of these systems were salvaged for possible use in future fermentation research. However, some of the materials from the pilot reactors seem to be unsalvageable and will probably be discarded.

Full Scale Plug Flow and Conventional Control Fermentors

By the end of June, 1979, the full scale plug flow and conventional control reactors concluded their steady state operation at 10 days HRT, 35°C, 10-12% TS manure feed. Steady state biogas production rates averaged $2.45 \text{ m}^3/\text{m}^3$ reactor/day (60 percent methane) with total volatile solids (TVS) destruction efficiency of 30.2 percent for the plug flow fermentor compared to $2.33 \text{ m}^3/\text{m}^3$ reactor/day biogas production (60 percent methane)

and a 26.2 percent TVS destruction efficiency for the conventional control. Both fermentors operated at the 10-day condition without noticeable signs of stress. But it is again apparent from the steady state data that the simplified, low cost, plug flow fermentor is capable of out-performing the completely-mixed conventional system in solids destruction and gas production, even at the higher hydraulic loadings. The 10-day HRT condition was the last experiment to be completed at 35°C.

Following this condition, both full scale systems were shifted in operation to a lower temperature, 25°C while fed 10-12% TS dairy manure (no bedding) at a 30 day HRT. The reactors were then operated at the lower temperature condition from the first week in July through October 15, 1979. As of mid-October, the 25°C reactors had just entered steady state in operation with respect to gas production. Data from the low temperature operation at 30 days HRT are presented in Table 10. Also presented in this table are steady state data from the three previous runs at the higher temperature of 35°C. In switching from 35°C to 25°C at 30 days HRT, both full-scale units experienced a decline in gas production of about 24 percent. It is interesting to note that, even at the lower reactor temperature, the full scale plug flow fermentor was able to achieve significantly higher rates of biogas production and solids destruction than the high-technology conventional control fermentor.

Cost Assessment and Economic Analysis Computer Model Development

An integral part of the final report and the farmers feasibility manual is the description of the economics of methane generation on the farm. During the summer months of 1979, two computer models were

TABLE 10. COMPARISON OF GAS PRODUCTION AND SOLIDS CONVERSION DATA FROM THE FULL SCALE PLUG FLOW AND CONVENTIONAL CONTROL FERMENTORS OPERATED ON DAIRY MANURE AT 35° AND 25°C.

		35°C			25°C	
		10-day HRT	15-day HRT	30-day HRT	30-day HRT	
Gas Production	vol/vol	2.33	2.13	1.13	0.86	Full Scale Completely Mixed Reactor
	l/gm VS _A	0.205	0.281	0.310	.266	
	ft ³ /lb VS _A	3.3	4.5	5.0	4.3	
Gas Composition	% CH ₄	60	55	58	58	
Solids Destruction	% TVS red.	26.2	27.8	31.7	16.2	Full Scale Plug Flow Reactor
	% TBVS red.	59.5	61.1	69.7	36.8	
Gas Production	vol/vol	2.45	2.33	1.26	0.96	
	l/gm VS _A	0.233	0.337	0.364	.283	
	ft ³ /lb VS _A	3.7	5.4	5.8	4.5	Full Scale Plug Flow Reactor
Gas Composition	% CH ₄	60	55	57	57	
Solids Destruction	% TVS red.	30.2	34.1	40.6	23.5	
	% TBVS red.	68.6	75.3	90.0	53.4	

formulated to carry out this analysis. One program was developed for use on a desk top computer (Hewlett Packard, model 9830) to allow the rapid calculation of the capital costs of plug flow reactors of varied dimensions, designs and capacities. The costing model was formulated by first performing a detailed, cost-element accounting of the Cornell plug flow fermentor, then developing equations to extrapolate these estimates to other plug flow fermentor systems of given design and capacity. Cornell's plug flow reactor, the example for the cost analysis, had a manure-handling capacity equivalent to 22 to 65 dairy cows when operated between 30 and 10 days HRT. The cost model was made applicable for reactor capacities between 25 and 500 dairy cows.

Capital costs associated with the construction of a plug flow reactor were divided into 18 categories or components. Costing elements and the basis for scale-up used on each of these items to estimate costs of other plug flow fermentor systems are summarized in Table 11.

The general costing approach taken here was to consider the plug flow reactor as an energy generation facility to be integrated into an existing liquid manure-handling system consisting of a barn scraper system, ram pump and a holding pond. This type of system is not uncommon, since many dairy cattle operations in the U.S. (particularly the larger ones) have adopted liquid-waste handling to control labor costs.

Examples of data generated from the cost assessment program are seen in Table 12 which gives a detailed breakdown of construction costs for 100 and 500 cow digesters, operated at 20 days HRT, 35°C. The highest cost items at both digester capacities are the insulation for the earthen basin (about 20% of total cost), labor (16%), and the flexible gas collection material (10%).

TABLE 11. BASES FOR SCALE-UP OF COST COMPONENTS OF PLUG FLOW FERMENTORS CON-
STRUCTED FOR ON-FARM GENERATION OF METHANE.

<u>Cost Component</u>	<u>Costs Associated With Cornell's Plug Flow System (32-Cow Capacity)</u>	<u>Basis for Scale-Up</u>
1. Excavation	\$ 364	Earth displaced to dig the basin and to install the underdrains
2. Underdrain	576	Gravel and pipe required, f(reactor dimensions)
3. Grading	309	f (reactor volume)
4. Wall Hypalon	679	f (reactor wall & floor areas)
5. Gas Cover Material	1,209	f (top surface dimensions)
6. Gas Cover Anchoring	1,164	Placed every 2 ft, 1 1/2 ft below liquid surface, f(reactor perimeter)
7. Basin Insulation	2,913	f (wall and floor areas, inches of foam glass insul. thickness)
8. Gas Cover Insulation	574	f (gas collection bag area)
9. Liquid Surface Insulation	105	f (moat and effluent end liquid surface areas, floating)
10. Water Heater	462	f (worse case reactor heating requirements, heating efficiency)
11. Reactor Internal Heat Exchanger	472	f (worse case heating required, diameter of pipe used, pump flow rates of recirculated hot water, black steel pipe assumed, 4" diam.)
12. Thermostats and Wiring	390	f (reactor volume)
13. Gas Transport Lines	200	f (reactor length)
14. Baffle	37	f (reactor width, depth)
15. Influent and Effluent Piping	1,357	Black steel, 8" diam, f (reactor length)
16. Equipment Housing	600	Floor area constant, 10 ft x 10 ft at \$6.00 per ft. ²
17. Labor	2,208	Using the Cornell system labor requirement as the reference for scale-up; 25% of labor - fixed at 60 man-hours 25% of labor - scaled up on basis of reactor perimeter
TOTAL	\$13,619	

TABLE 12. CAPITAL COST COMPONENTS OF PLUG FLOW REACTORS OF 100 AND 500 COW CAPACITIES OPERATED ON DAIRY CATTLE MANURE AT A 20 DAY HYDRAULIC RETENTION TIME.

Cost Component	100 Cows		500 Cows	
	Dollars	% of Total	Dollars	% of Total
Excavation	786	3.5	3136	5.3
Underdrain	891	4.0	1945	3.3
Grading	668	3.0	2666	4.5
Wall Hypalon	1064	4.8	24.6	4.1
Gas Cover Material	2236	10.0	6019	10.1
Gas Cover Anchoring	1642	7.4	2857	4.8
Basin Insulation	4711	21.1	11257	18.9
Gas Cover Insulation	1366	6.1	4542	7.6
Liquid Surface Insulation	153	0.7	295	0.5
Water Heater	678	3.0	1951	3.3
Heating Pipes	1218	5.5	5500	9.2
Thermostats and Wiring	910	4.1	4550	7.7
Gas Lines	300	1.3	500	0.8
Baffle	66	0.3	169	0.3
Influent/effluent Piping	1500	6.7	1500	2.5
Equipment Housing	600	2.7	600	1.0
Labor	35.2	15.8	9560	16.1
Base Cost	22301		59463	

Total capital costs for digester systems constructed on New York State dairy farms are presented in Table 13. Capital costs for the plug flow reactor design range from about \$120 per cow for 500 cow operations to about \$500 per cow for a 25 cow unit. From the capital costs in Table 13 it can be seen that there is great flexibility in selecting a reactor size to match anticipated biogas demands without significantly increasing the capital cost. For farm operations less than 100 dairy cows, it appears that the basin size of an earthen fermentor is not a highly cost-sensitive design variable. Expansion of the simplified plug flow digester from 15 to 20 days (a 33% increase in volume) would result in an additional cost of less than \$2,300, a 7 to 8 percent increase, for the smaller dairy farms. The modest nature of the cost increase in this case is due to the relatively low construction cost of the reactor basin itself as compared to the fixed costs of the system such as heating equipment, piping, electrical work, fixed labor, equipment housing, etc. Even at the 500-cow scale, an additional capital expenditure of only 15 percent would be required for this kind of increase in reactor volume.

The economics of methane generation from cattle waste were examined for various sizes and applications of the Cornell plug flow fermentor by estimating net energy production rates from the heat balance model, by calculating capital costs with the reactor costing model, and by inputting the data from these programs into an economics model formulated by Ecotope Group (Coppinger, et al., 1978). This model has been programmed for use on the Hewlett Packard HP 9830 desk top computer and for use on the Hewlett Packard HP 97 and Texas Instruments TI58 and TI59 programmable calculators. The major assumptions used in the economic analysis model are listed in Table 14.

TABLE 13. TOTAL CAPITAL COSTS FOR PLUG FLOW REACTORS OPERATED AT 15 AND 20 DAYS HYDRAULIC RETENTION TIME.

<u>Dairy Cows</u>	<u>15 Days HRT</u>		<u>20 Days HRT</u>	
	Dollars	\$/Cow	Dollars	\$/Cow
25	11,460	458	12,387	495
50	14,551	291	16,334	327
100	19,895	199	22,303	223
200	29,336	147	33,680	168
300	36,988	123	42,768	143
400	44,129	110	51,147	128
500	50,755	102	59,464	119

TABLE 14. ASSUMPTIONS AND INPUTS USED IN THE ECONOMIC ANALYSIS OF SIMPLIFIED METHANE GENERATION.

<u>Parameter</u>	<u>Value</u>	<u>Comment</u>
Fraction of Net Biogas Utilized	>90%	
Interest Rate	10%	
Inflation Rate	7%	
Fuel Escalation Rate	15%	Average yearly price increase since 1973.
Cost of Energy Displaced	\$5.90/GJ	Fuel oil and propane prices in Upstate New York.
Life of Facility	15 years	Estimated life of expendable materials.
Life of Loan	15 years	Same as the life of the facility.
Tax Bracket	20%	Federal and State.
Capital Credits:		
Capital Investment	7% of CC*	Tax Credits.
Clean Water Act (EPA)	12% of CC	Total Credit $\leq$ \$3,500.
Renewable Energy	30% of Initial @2,000 CC 20% of Balance of CC	Total renewable energy tax credit not to exceed \$2,000.
Depreciation	Straight Line	Taken over 15 years.

* CC = Capital Cost of the Plug Flow Anaerobic Fermentor.

Typical results of the economics of biogas generation from 20-day HRT fermentors of varied capacities operated on 11-13 percent dairy manure at 35°C are presented in Table 15. The economics information of Table 15 indicate that if nearly all of the biogas can be utilized, the cost of converting cattle manure to methane can be competitive with current prices for propane and fuel oil (priced at about \$5.25 per GJ). Energy production costs from methane generation appear especially attractive for farms of 50 head or more. For dairy farms of 100 cows or larger it is estimated that methane can be generated with simplified anaerobic systems at a cost of about 50-60 percent of current liquid fuel prices. Payback periods on these systems range from about two years for a 500 cow unit to seven years for a 25 cow digester. It is noteworthy that the U.S. tax credits for methane generation may already be substantial, particularly if anaerobic fermentation on the farm is recognized by U.S. regulatory agencies as both an alternative energy source and an effective process for pollution control. Such credits, based on existing laws, could defray up to 20 to 30 percent of the initial capital cost.

The preliminary economic analysis of the operation of the plug flow fermentor on dairy manure indicates that biogas can be produced on dairy farms of 25 to 500 cows at stable costs lower than current prices for propane and fuel oil. As world energy prices continue to climb, the economics of on-farm methane generation will continue to look more and more attractive. It should be pointed out, however, that although the economics appear promising, the ultimate value of the biogas will depend upon the degree to which high-priced fuels can be displaced by fermentor gas on the farm. The economic analysis presented here assumes that more than 90 percent of the yearly biogas could be utilized. The specific costs of

TABLE 15. SUMMARY OF THE ECONOMIC ANALYSIS ON THE PLUG FLOW ANAEROBIC FERMENTATION OF DAIRY MANURE USING THE ECOTOPE MODEL.

<u>Item</u>	<u>25 Cows</u>	<u>50 Cows</u>	<u>100 Cows</u>	<u>500 Cows</u>
Inputs:				
Capital Cost, Dollars	12,974	16,900	22,300	54,000
Tax Credits, Dollars	4,839	5,069	6,050	9,053
Maintenance, Dollars	454	590	781	1,899
Operating Costs, Dollars	356	512	825	3,325
Net Energy Production, GJ/year	215	452	917	4,520
Results:				
Energy Production Cost, Dollars/GJ				
With Operating Labor	\$6.80	\$4.68	\$3.40	\$2.29
Without Operating Labor	\$5.14	\$3.55	\$2.50	\$1.55
Payback Period, Years	6.9	4.9	3.6	2.2

* Energy Production Costs were calculated with and without the costs of farm labor involved in the operation of the fermentor. Operating labor costs may not be recognized by the farmer particularly if he is not forced to hire additional personnel and if he is able to cover the additional labor requirement through more efficient time management.

utilizing the biogas were not taken into account because such schemes may vary widely in expense and complexity: from a simple retrofit of biogas burners in existing propane space heaters and water heating units, to the outright purchase of new biogas utilizing equipment. It is intuitive that if biogas can be generated on the farm at a cost far below current energy prices, a certain degree of gas wastage can be tolerated; the data in Table 15 indicate that for dairy farms of 50 cows or greater, more than 20 to 40 percent of the net biogas would have to be unused before methane production costs would begin to appear noncompetitive with liquid fuels.

The availability of biogas utilization options should, on the whole, enhance the implementation of anaerobic fermentation on small farms. The easiest and most direct usage of biogas is through water and space heating (involving direct burning). For larger agricultural operations (> 100 cows) additional investment into other biogas utilization systems may be warranted. Electricity generation from biogas-driven internal combustion engines may be attractive, since a variety of electrical farm equipment, refrigeration units, and appliances could then be indirectly operated on fermentor gas. Gas compression and storage may involve a substantial capital investment; but such systems could allow an improved match-up between farm energy demands and biogas generation patterns. Agreements with utilities for the sale of excess biogas or farm-generated electricity may also be beneficial in the future; such arrangements could virtually insure total utilization of the biogas. More research and analysis on the utilization and storage of biogas on small farms is undoubtedly needed.

Dry Fermentation

In the Fall of 1979, some effort was placed on the planning of a bench scale study to investigate certain aspects of the proposed dry fermentation study as outlined in the new Methane Project proposal submitted to D.O.E. A preliminary testing program was developed by mid-October. Dr. Jewell would be consulted at the beginning of every experimental test. The main topics planned for the bench scale dry fermentation study include thermophilic fermentation, NaHCO_3 versus CaCO_3 buffering, and volatile acid stripping.

After 336 days of operation, the 5.0 m³ mesophilic, pilot-scale dry fermentor charged with wheat straw at a solids concentration of about 25 percent was producing biogas at a rate of 8 ft³ per day with a methane content of 54 percent. This study has been described in more detail in the eleventh quarter progress report. The dry fermentor will continue in operation until one year has elapsed, at which time the unit will be opened and the contents examined. Of particular interest will be the physical appearance of the material and the presence of any large pockets of undigested material.

Final Report

During the period from June 16 to October 15, 1979, final report preparation activities continued at a steady and productive pace. Computer simulations of energy balances on anaerobic fermentors of varied capacity and design were carried out during the summer months. As previously mentioned, the cost assessment economic analysis programs that were developed were used to closely examine the effects of reactor construction, capacity and operation on the costs of producing biogas energy on the farm. Consultants David Baylon of Ecotope Group and Tom Abeles of I.E. Associates

provided the Cornell methane project with additional perspectives to the economic analysis and suggested various approaches of evaluation. The latest data from the operation of the full scale plug flow and conventional control reactors at Cornell were analyzed and included in the experimental write up. By mid-October, most of the major technical sections of the final report were developed to the rough-draft stage. Work is continuing on the preparation of tables, figures and graphics.

Feasibility Manual

In the months following the end of the twelfth quarter period, information gathering and literature analysis for the development of the technical sections of the farmer's feasibility manual progressed rapidly. Of the seven total chapters, four and one-half were completed in first draft form by mid-October.