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

Eleventh Quarter Progress Report for Period From
December 16, 1978 to March 15, 1979

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

SUMMARY

The Cornell University project on production of methane from agricultural residues has as its main 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 next-to-last quarter of this study.

Five different types of anaerobic fermentor reactor designs are presently being operated, with the majority of effort focussed on two full scale reactors (both about 35m³) designed to process the residues produced by 65-cow dairies. 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 nearly 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. Preliminary analysis of the data indicates more efficient solids conversion with the plug flow design (41 percent TVS destruction efficiency) than with the completely mixed full scale system (31.7 percent TVS destruction efficiency) when operating at a 30-day hydraulic retention time at 35°C.

Although analysis of the thermal data is incomplete, comprehensive heat loss studies were conducted during the cold period. The efficiency of the boiler-hot water heating system varied between 40 and 55 percent. The net energy production during the coldest conditions (worst case) was estimated to be 44 percent at a 15-day HRT at 35°C with the low-cost plug flow system.

Considerable operational problems with the full scale systems occurred during the coldest winter period; but these problems were not caused by the weather. Both units have been out of operation for several weeks but were back in full scale operation by mid-March.

Activities in the next quarter will conclude all pilot plant analysis and most of the full scale testing. It is anticipated that completion of testing the full scale units and preparation of the final reports will take place during the 13th quarter (summer 1979).

REPORT OUTLINE

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

INTRODUCTION

The concern for U.S. energy supplies was heightened during the last three months because of the recent events in the Middle East. The abrupt cutoff of Iranian oil during this time of crisis served to underscore the serious negative implications of a continued, increasing dependence on this volatile part of the world for future oil supplies that are a key part of a thriving U.S. economy. There is 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 eleventh 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 2.5 to 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 eleventh quarter, extending from December 16, 1978, to March 15, 1979, have included the following:

1. Collection of steady state data from the full scale plug flow reactor and control unit operated at 30 days HRT, 35°C and 10-12% TS manure feed.
2. Replacement of the internal heat grid on the full scale plug flow reactor under adverse subzero weather conditions.
3. Replacement of the internal gas collection liner of the full scale conventional control reactor.
4. Initiation of the full scale plug flow reactor into the next scheduled condition of 15 days HRT, 35°C, 10-12% TS manure feed.
5. Continued experimentation with bedding addition to the dairy manure feedstock of the pilot scale plug flow fermentor. During this feeding mode steady state data was obtained at 15 days HRT and 35°C, and 30 days HRT and 25°C.
6. Collection of steady state data from the random mix reactor operated on manure and bedding (straw) at 35°C, 16 days HRT, fed and mixed every four days, 11-13% TS feed. Using the same feedstock, the reactor was then changed in its operation to 25°C, 28 days HRT, fed and mixed once per week.

7. Startup and operation of a semi-solid reactor operated with initial solids content of around 30%.
8. The initial planning of the content and format of the final report, including the preparation of a detailed, preliminary outline for this document.

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. Throughout the eleventh quarter, the pilot and full scale fermentors were to continue in their operation, progressing well into the final conditions for each reactor. The pilot scale random mix reactor (5.0 m^3) was to conclude its experimental testing with manure and bedding feed at low temperatures and cease in 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 eleventh quarter was the continued operation of the full scale plug flow and conventional control reactor (34 m^3) on a manure and bedding feedstock at a lower temperature (25°C).

Present Status

Long-term operation of the full scale low-cost reactor has now been ongoing continuously for just less 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. The operation of the pilot scale reactors has thus far adhered closely to the work plan. However, the full scale demonstration phase has had delays due to the adversity of severe winter weather during the initial construction (December 1977 - March 1978) and some reactor modifications that were made during the last quarter. The revised experimental plan was drafted to accelerate the testing program and to narrow the schedule gap, as shown in Figure 3. Progress

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

FIGURE 2. CORNELL UNIVERSITY METHANE PROJECT WORK PLAN FOR 1977-1979.

Figure 3. EXPERIMENTAL TESTING PROGRAM

in reference to the new schedule is indicated, showing a 2 1/2 month overall delay behind the accelerated work plan.

Progress review meetings were held with the methane project group on a weekly basis throughout the eleventh quarter for periodic progress review and discussion of various tasks and problems encountered during this demonstration period in the coldest season of the year. The notes and minutes from these sessions are available upon request from the investigators.

Pilot Scale Random Mix Reactor

During the latter weeks of the tenth quarter period, the PVC internal heat exchanger of the pilot scale random mix unit was replaced with a steel heat grid because of some previous mechanical problems described in the Tenth Quarter Progress Report (December 15, 1978). Following a repair period of 15 days, the random mix reactor was restarted by filling the system with 900 gallons of effluent from the pilot scale plug flow reactor and with 300 gallons of manure and straw mixture. Throughout most of the eleventh quarter the random mix unit was operated on a manure and straw feed mixture (11 to 13% TS), 16 days HRT, 35°C and fed once every four days. 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 $2.0 \text{ m}^3/\text{m}^3$ reactor/day ($1.2 \text{ m}^3/\text{m}^3/\text{day CH}_4$) with a concomitant TVS destruction of 26.9 percent. A comparison of reactor performances at this condition and other previous operating modes is provided in Table 1. It is probably that the difference in TVS destruction efficiency between the two long HRT tests is more related to the biodegradable fraction change than a mixing effect.

During most of the experimental period when the random mix reactor was operated at 16 days HRT, 11-13% TS chopped straw and manure feed, and 35°C, the gas production and solids destruction performance was maintained at constant and uniform levels. Within twenty days of the end of the experimental run, however,

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
Feeding Frequency	once/day	once/7 days	once/4 days	once/4 days
Mixing Frequency	once/10 days	once/7 days	once/4 days	once/4 days
Days of Operation	104	90	52	70
Average Gas Production				
m^3/day	10.1	6.4	8.2	10.0
$\text{m}^3/\text{m}^3 \text{ reactor/day}$	2.0	1.3	1.6	2.0
Methane Production				
m^3/day	6.3	3.7	4.9	5.9
$\text{m}^3/\text{m}^3 \text{ reactor/day}$	1.3	0.74	0.98	1.2
Effluent pH	7.8	7.7	7.6	7.8
TVS Destruction, Percent	37.0	31.4	28.7	26.9

the reactor exhibited a significant decrease in gas production from an average value of about 10.0 m^3 per day to 5.2 m^3 per day. Other parameter measurements for pH, volatile acids and alkalinity did not suggest a distressed situation for the fermentation process during the low-performance period, thereby indicating that a variation in manure biodegradability may have caused the observed decrease in gas production. Throughout this bedding addition condition, no significant amount of solids accumulation was observed. This is an important observation in relation to minimum mixing needs for reactors using animal manures with straw and hay bedding.

Upon completion of the bedding addition study at 35°C , the random mix reactor operation was changed to a lower temperature, 25°C , using the same straw-manure feedstock. The reactor is presently operated at a 28-day HRT, 11-13% TS feed, feeding and mixing once per week. Gas production and trouble-free operation at this lower temperature is surprisingly good. The experimental progress for this unit is nearly on schedule.

Pilot Scale Plug Flow Fermentor

The pilot scale plug flow fermentor completed two experimental runs during the eleventh quarter while operating on feed mixtures of manure and bedding. After completing an experimental run at a feeding mode of 11-13% TS wood chips and manure influent, 30 days HRT, and 35°C , the same reactor conditions were repeated in the first portion of the eleventh quarter using chopped straw (cut into 2.5 cm lengths) for bedding addition at a blending rate of 0.68 Kg/cow/day (1.5 lbs/cow/day). Under this mode of operation a gas production rate of $4.67 \text{ m}^3/\text{day}$ ($0.84 \text{ m}^3/\text{m}^3$ reactor/day) was observed with a total volatile solids destruction efficiency of 35.2 percent. In the course of the 35°C experiment, a fibrous float formed to a thickness of 0.15 m (6.0 inches) at the feed end of the plug flow unit, increasing through the reactor to a depth of 0.76 m (2.5 feet) at the effluent end. Solids measurements at various points in the reactor and a soluble tracer study indicated

that eventually only 60 percent of the total volume of the reactor was functional in fermentation. The data also suggested that the float formation rate reached steady state in that the depth of the float remained stable for several weeks. When solids ceased to accumulate in the float, steady state data was obtained from the pilot scale plug flow fermentor.

The next operating condition was established at a 15-day HRT, 35°C and 11-13% TS manure and chopped straw feed. Once again, at the shorter retention time the depth of the floating straw solids remained constant and, after a month of operation, steady state from this condition was also obtained according to schedule, thus concluding the bedding addition study at 35°C.

Steady state data from three experimental runs comprising the bedding addition study conducted at 35°C are presented for comparison purposes in Table 2. In general, the wood chip addition in the reactor seemed to produce more methane than the chopped straw addition experiments conducted under the same temperature and hydraulic retention time conditions. The nature of the bedding types used and the fact that the wood chips were added at a higher rate (1.36 Kg/cow/day or 3.0 lbs/cow/day) than those rates applied to the straw addition experiments (0.68 Kg/cow/day or 1.5 lbs/cow/day), thus resulting in a higher influent solids concentration for the wood chip experiments, were partially responsible for the difference. Float accumulations occurred with the straw addition experiments, resulting in only 60 to 70 percent of the fermentor volume being usable. Hence, the hydraulic retention time of the system was significantly less than 30 and 15 days, respectively. It is particularly interesting to note, however, that the highest methane gas production rates were observed with the straw-addition experiment employing a 15-day HRT to the pilot scale plug flow reactor while the system continued to maintain the same float solids depth throughout the testing period. At an estimated effective hydraulic retention time of 10-12 days, the pilot scale plug flow reactor gas production rate was an impressive $1.0 \text{ m}^3/\text{m}^3 \text{ reactor/day}$ in biogas produced.

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

*Data from the tenth quarter period.

**Data from the eleventh quarter period.

Following the collection of steady state data for the concluding bedding-addition experiment at 35°C, the plug flow reactor temperature was lowered to 25°C. Presently, the plug flow reactor is operating at a 30-day HRT, manure and straw feedstock (11-13% TS), 25°C. Testing for this unit is close to schedule. Preliminary gas production rates are only slightly less than comparable conditions at 35°C.

Full Scale Plug Flow Fermentor and Completely Mixed Control Unit

Early in the eleventh quarter, the full scale plug flow and conventional control fermentors reached steady state under operating conditions of 35°C, 30 days HRT, and 10-12% TS dairy manure feed. A summary of the entire body of steady state gas production and solids destruction data obtained from these units is presented in Table 3 as compared to performances observed from bench and pilot scale reactors. Final data comparisons in Table 3 indicate that the full scale plug flow and conventional control fermentors operated at gas production and solids destruction efficiencies comparable to those obtained with the smaller reactor prototypes operated at the bench and pilot scale level. Both full scale reactors produced biogas at rates of 1.26 and 1.13 m³/m³ reactor/day for the plug flow and conventional control systems, respectively. A detailed comparison of the steady state operation of the two full scale systems is given in Table 4.

The operation of the full scale plug flow and conventional control fermentors through Ithaca winter weather conditions has allowed a better understanding of the problems associated with conserving energy in these systems for temperature maintenance when operating in cold climates. The determination of the rate of heat lost from the low-cost full scale plug flow reactor is necessary to the calculation of the net energy production that can be derived from the system at various times of the year. The winter season becomes most crucial to the overall energy balance of anaerobic fermentation systems since low ambient air temperatures generally produce a greater demand on the farm for heating energy just when the

TABLE 3. COMPARISON OF RESULTS OBTAINED FROM VARYING SIZES OF REACTORS AT 35°C and 30-day HRT.

PLUG FLOW REACTOR DESIGN

Scale	Gas Production			Gas Comp. (% CH ₄)	% TVS Reduction	Reactor Volume (ft ³)
	vol/vol	l/gm VS _A	ft ³ /lb VS _A			
Bench ¹	0.91	0.357	5.7	56	49.1	0.1
Pilot	1.10	0.333	5.3	61	25.7	200
Full	1.26	0.364	5.8	57	40.6	1360

COMPLETELY MIXED REACTOR DESIGN

Scale	Gas Production			Gas Comp. (% CH ₄)	% TVS Reduction	Reactor Volume (ft ³)
	vol/vol	l/gm VS _A	ft ³ /lb VS _A			
Bench ²	0.92	0.246	4.0	64	32.0	0.1
Bench ³	0.81	0.350	5.6	63	36.0	0.5
Pilot	--	--	--	--	--	--
Full	1.13	0.310	5.0	58	31.7	1250

NOTES:

1. UHD Reactor Run at 8% TS
2. Control Reactor for Pilot Scale Plug Flow Run at 12% TS
3. Morris Data Run at 8% TS

TABLE 4. COMPARISON OF STEADY STATE OPERATION OF FULL SCALE DAIRY MANURE DIGESTION SYSTEM

	Completely Mixed Reactor	Plug Flow Reactor
Condition, HRT, days	28.5	28.1
Feed Rate, gal/day	328	363
Days of Operation	111	111
Days of Steady State	57	57
Total Solids, gm/l		
Influent	119.5	111.7
Effluent	87.4	72.2
Reduction	32.1	39.5
Reduction, %	26.9	35.4
Volatile Solids, gm/l		
Influent	103.6	96.9
Effluent	70.8	57.6
Reduction	32.8	39.3
Reduction, %	31.7	40.6
Biodegradable Volatile Solids		
Refractory Fraction	0.55	0.55
Refractory Solids, gm/l	57.0	53.3
Influent, gm/l	46.6	43.6
Effluent, gm/l	13.8	4.3
Reduction, gm/l	32.8	39.3
Reduction, %	70.4	90.1
Gas Production (all values at STP)		
ft ³ /day	1412	1717
% CH ₄	58	57
ft ³ CH ₄ /day	820	980
Gas Production Predicted From Measured Biodegradable Volatile Solids Destruction		
ft ³ CH ₄ /day	722	957
Energy Produced, Btu/day	7.86 x 10 ⁵	9.71 x 10 ⁵
Energy Required, Btu/day	4.96 x 10 ⁵	11.32 x 10 ⁵
Energy Used in System, % Total	63	117

digester itself requires more of its own biogas to maintain temperatures at 35°C. In order to determine the energy demand of the full scale reactors, conducted heat loss tests were initiated consisting of simply shutting down the boiler, ceasing wasting and feeding for a 48-hour period, and measuring the resultant decrease in temperature of the reactor contents. Three heat loss studies were performed on the full scale plug flow reactor, one test performed before the top flexible liner was insulated and two conducted after three inches of fiberglass insulation and a protective sheet of hypolon rubber was laid over the gas collection cover. Conducted heat loss testing was also conducted on the full scale conventional control fermentor.

The data from these heat loss studies, presented in Table 5, show the significant benefit to be realized in insulating the top gas collection liner of the reactor. This is most convincingly seen from the fact that the observed digester heat loss of 496,000 Btu/day at an ambient air temperature of 33.5°F was reduced to 359,000 Btu/day even though the average air temperature had dropped from 1°C to minus 18°C. Specifically, heat loss calculations predicted a decrease in heat loss from the digester gas cover of more than 82 percent leading to a dramatic reduction in the total conducted heat loss by about 58 percent in spite of colder ambient air temperatures. As seen in Table 5, the overall conducted heat loss was reduced by about 28 percent. There are two possible reasons for the differences in the predicted and actual energy savings realized. First, the effluent overflow zone of the reactor, insulated during the first heat loss test, was only partially insulated during the second heat-loss run; the heat loss value given for the effluent zone is an estimate and could range as high as 200,000 Btu for the second trial. Second, the insulation blanket for the flexible cover had been disturbed during a previous repair operation, thereby possibly reducing its total effectiveness to conserve heat.

The total energy input required relative to the energy produced each day was estimated at 63 percent for the first test and 44 percent for the second.

TABLE 5. HEAT BALANCE DATA OBTAINED FOR THE PLUG FLOW FERMENTOR

Parameter	Plug Flow Reactor Heat Loss Tests	
	Uninsulated Liner	Insulated Liner
Digester Temperature, °F	95	95
Ambient Temperature, °F	33.5	0.6
48-Hour ΔT, Digester, °F	12	8.7
<u>Calculated Heat Losses, Btu/day</u>		
Heat Loss to Soil	29,600	36,700
Heat Loss to Air		
Cover	437,000	76,700
Moat	25,000	38,900
Baffle Zone	6,500	58,900
Total Conducted Heat Loss	498,000	211,000
<u>Observed Conducted Heat Loss, Btu/day</u>	496,000	359,001
Observed/Calculated Heat Loss	0.99	1.70
Hydraulic Retention Time, days	30	15
Energy to Heat Raw Feed, Btu/day	143,000	303,000
Total Energy Required (Observed), Btu/day	639,000	662,000
Biogas Energy Produced, Btu/day	971,000	1,500,000*
Ratio Btu Required/Btu Produced	0.66**	0.44**

* Anticipated energy production rate based on past observations of methane production rates from the pilot scale plug flow fermentor operated at 95°F, 15 days HRT and 10-12% is dairy manure feed.

** This ratio does not take into account the overall heat transfer efficiency of the boiler and digester heat exchanger.

The measured thermal loss characteristics are useful in examining the net energy production capability of the system under adverse conditions. A comparison of the low-cost plug flow system operational characteristics to those of a well insulated completely mixed system is given in Table 6. Note that the net energy production at a 15-day HRT when the air temperature averages less than minus 18°C is 44 percent of the total production. This value is based on actual increased thermal properties, but on gas production data extrapolated from pilot data. This data is illustrated in Figure 4.

Previous pilot plant operation at 25°C indicates that this may be an optimum temperature for units susceptible to large energy losses. The present operation of the two pilot units and the eventual operation of the full scale units at 25°C as the last test condition will confirm the advantages. A comparison of the impact of the operation of the plug flow unit at 35°C and 25°C is shown in Figure 5. Note the significant increase in net energy that appears to result when a lower temperature is chosen.

At certain times during the eleventh quarter, both full scale units were under repair, though for different reasons. About midway through the quarter, the PVC heat exchange grid inside the full scale plug flow unit experienced excessive leaking. It was then decided to remove the PVC grid and replace this heating system with black steel pipe, four inches in diameter. Personnel from a number of other research projects in the Department of Agricultural Engineering assisted Methane Project members in the repair of this system.

A major concern was that the subzero temperatures of -30°F to -10°F and wind conditions could make installation very difficult. Another concern was whether the flexible liner material could be handled without causing cracks and holes during the cold when removed from the top of the reactor and during replacement. After pumping the plug flow reactor empty, the research team removed the PVC gas collection system over a two-day period and then installed the steel pipe grid over a period of about a week. The cover was replaced and within 10 days of

TABLE 6. COMPARISON OF ENERGY GENERATION WITH THE TWO FULL SCALE SYSTEMS OPERATING UNDER COLD CONDITIONS

Parameter	Plug Flow Reactor			Completely Mixed Reactor		
	30 Day HRT	15 Day HRT*	15 Day HRT*	30 Day HRT	15 Day HRT	15 Day HRT*
Ambient Air Temperature, (°C)	1	1	-18	1	1	-18
Heat Loss to Surroundings, (Btu/day)	496,000	111,000	170,000	78,250	78,250	123,900
Feed Temperature, (°F)	50	50	40	50	50	40
Heat Loss to Heat Feed, (Btu/day)	143,000	246,000	303,000	130,340	242,210	302,760
Total Heat Required, (Btu/day)	639,000	357,000	473,000	208,490	320,460	426,660
Total Heat Supplied, (Btu/day)	1,132,000	638,000	845,000	496,000	736,000*	1,015,860
Heating System Efficiency, (%)	56	56	56	42	42*	42
Total Biogas Produced, (ft ³)	1717	2500	2500	1412	2500*	2500
Total Energy Produced, (Btu/day)	971,000	1,500,000	1,500,000	786,000	1,500,000*	1,500,000
Energy Used, (Btu/day)	1,132,000	638,000	845,000	496,000	736,000*	1,015,860
Net Energy, (Btu/day)	0	862,000	655,000	290,000	764,000*	484,140
Energy Used, (% of Total)	117	43	56	63	49*	68
Net Energy, (% of Total)	0	57	44	37	51*	32

*Calculated values from measured thermal characteristics.

Figure 4. Observed gross biogas energy generation and resulting system total energy demands. All values based on measured thermal losses; losses correlated to 0°C in all cases except for two measured at minus 18°C. Note that the 30 day HRT plug flow reactor tests conducted without an insulated top resulted in an energy demand greater than the gross production.

Figure 5. Annual temperature variations in New York and its influence on the net energy produced as calculated from thermal loss characteristics with a fermentor system operating on a 50 cow dairy residue feed. Two systems are illustrated operating at 35°C and 25°C.

the initiation of repair the reactor was back into operation. Startup consisted of filling the plug flow reactor up with manure and heating. The unit attained a temperature of 35°C in about three days, indicating a well-functioning heat exchanger. The speed with which this major repair task was completed, under artic-like winter weather conditions, demonstrated a high degree of flexibility and serviceability of the Cornell plug flow design.

The full scale conventional control fermentor also required major repairs during this quarter. During a shift of conditions from 30 days to 15 days HRT, this unit experienced excessive foaming to the extent that large quantities of liquid were displaced from the reactor. More importantly, the foam that was produced apparently worked its way between the rubber-like liner and the reactor walls. A buildup of pressure occurred which apparently collapsed the liner. This reverse pressure collapsed the steel gas collection pipes and broke the PVC heat grid in several areas. When this occurred, plans were made to to clean the reactor out and repair the gas collection liner and to replace the PVC heat pipes with steel.

Unfortunately, the onset of extremely low temperatures coincided with the operational problems, and the lack of operation caused a number of the effluent valves and pipes to freeze, significantly adding to the workload and difficulties of getting the units back into operation. It is anticipated that this unit will be back in operation at a 15-day, 35°C condition by mid-March.

Currently, the plug flow reactor is operating at a 15-day HRT, 35°C and 10-12% TS manure feedstock. The full scale demonstration effort is running about three months behind the revised testing schedule.

SEMI-SOLID ANAEROBIC FERMENTATION OF AGRICULTURAL RESIDUES

An ongoing Ph.D. research study by Wujcik is presently focussing on the role of water in methane production. Using information developed in this study, a 5.0m³ mesophilic pilot scale reactor using wheat straw was started to review the potential of generating methane from solids with small amounts of water.

The straw reactor was originally started at about 30 percent solids, and this was too dry, as noted by the rapid decline of gas production after initial startup. Water was added to decrease the solids content to about 25 percent, which was the target level of moisture. Gas production started at this point and has been producing between 450 and 1200 liters of gas with 50+ percent methane for nearly four months. This corresponds to a gas production rate of 0.10 to 0.25 volumes per volume of reactor per day.

In addition to this pilot scale digester, two small bench scale control reactors were also placed into operation to analyze the effect of semi-solid fermentation under a more closely controlled environment. Both reactors were 2.5 liters in volume and were kept in a 35°C environmental chamber. The first reactor was a small duplicate of the pilot scale digester. It was started at 30% T.S. It also experienced a rapid decline in gas production after initial startup, at which time water was added to decrease the total percent solid to 25%. A second 2.5 liter bench scale digester was also started at this time; this reactor had an initial concentration of 10% T.S. A summary of data from all three reactors appears in Table 7. As is shown, the bench scale 25% T.S. reactor has performed slightly better than its pilot scale counterpart. At the time of this writing it has experienced a T.V.S. reduction of 42.9%, as compared to 24.6% reduction in the pilot scale digester. In addition, the biogas

TABLE 7.

SEMI-SOLID REACTOR PERFORMANCE---COMPARISON OF
PILOT AND BENCH SCALE DIGESTER PERFORMANCE

Parameter			Pilot Scale Semi-Solid Digester 50 = 25% TS	Bench Scale Semi-Solid Digester 50 = 25% TS	Bench Scale Semi-Solid Digester 50 = 10% TS
Days of Operation			119	112	118
Reactor Volume (ℓ)			4,955	2.5	2.5
Total Biogas Produced (ℓ)			82,643	82.08	80.33
Total CH ₄ Produced (ℓ)			38,175	34.46	46.68
Avg. % CH ₄ (After Startup)			54.0	57.0	58.1
% TVS Destruction Pred. From CH ₄ Produced*			24.6	42.9	52.9
Initial Feed Comp.	Straw	gms	365,470	180	180
		T.S. (gms)	328,923	162	162
		T.V.S. (gms)	302,609	149	149
		% T.V.S./TS	92	92	92
	Manure	gms	419,768	210	450
		T.S. (gms)	33,687	16.8	36
		T.V.S. (gms)	27,337	13.6	44
		% T.V.S./TS	81.2	81.2	81.2
	H ₂ O	gms	764,570	460	1350
	NaHCO ₃	gms	25,424	10.8	27.0

*Calculations on Following Basis: $1.25 \frac{\text{gms COD}}{\text{gm VS}}$ and $5.62 \frac{\text{ft}^3 \text{CH}_4}{\text{lb COD}}$ destroyed

produced from this reactor after startup contains slightly more methane than the pilot scale reactor--57% as opposed to 54%. It is hypothesized that the superior performance of the bench scale reactor is due to the fact that this reactor is shaken daily, which has allowed the free water in the reactor to come in intimate contact with the rest of the reactor contents. Because of the size of the pilot scale reactor, intimate contact between the free water and the straw solids is difficult to maintain. In this reactor the free water will drain to the bottom of the reactor and is periodically recycled back to the top of the digester. However, because of the size and limited recycle capabilities, the liquid has probably not reached all of the reactor contents. Therefore, it would be expected that degradation in the pilot unit would be slower than in the bench scale system.

Data from the 10 percent T.S. bench scale reactor is also shown in Table 7. The straw solids in this reactor are completely immersed in the liquid. Thus as would be expected, the gas production rates for this reactor are higher than for others. At the time of this writing this reactor has experienced a 52.9 percent TVS destruction. It is, for all practical purposes, biologically inactive since little gas is being produced.

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. This document will not be an extensive or comprehensive set of instructions on the construction of anaerobic fermentation systems, but rather a decision 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. Currently, the Methane Project does not have sufficient manpower to give adequate attention to the manual and yet conclude the remaining experimentation, analyze the data, and write the final report. Some thought, however, has been given to using certain consultants to assist in the preparation of certain sections of the design manual. Thus far, progress on the preparation of the manual is ahead of schedule.

FUTURE ACTIVITIES

In the early part of the next quarter, the pilot scale plug flow and random mix fermentors will complete the bedding addition studies, thus fulfilling all test conditions covered under the existing contract to D.O.E. By the end of the twelfth quarter both pilot units will be discontinued in operation, pumped out and cleaned.

During the first few weeks of the next quarter, the conventional completely mixed control reactor will be operating at a 15-day HRT at 35°C. For most of the twelfth quarter, both full scale reactors will progress through the accelerated testing program. The next condition of 10-12% TS manure feed, 35°C, and 15 days HRT should be completed about midway through the quarter. At that time the solids accumulation data from the pilot scale plug flow reactor will have been thoroughly analyzed, providing the basis for determining whether bedding should be added to the full scale, unmixed, plug flow fermentor while operated at 35°C. In light of the plugging problems encountered with the pilot and bench scale unmixed systems operated at this temperature, it may be advisable to postpone or eliminate this testing condition in lieu of demonstrating the long-term suitability of bedding addition with this unit operated at 25°C.

Laboratory experience with the pilot units have indicated little problem with float formation at the lower temperatures.

In the next three months there will be a major shift of manpower from experimentation and demonstration to the preparation of the final reports. Upon conclusion of the operation of the pilot reactors, minimum manpower will be operating the two full scale systems while the majority of the project personnel will be involved with the data analysis and the preparation of the final report. The detailed outline already prepared for this report will serve as a guide to content and format. Data analysis for the next quarter will include continued definition of the performance characteristics of the full scale and pilot scale

simplified reactors and close examination of the total energy balance on the full scale plug flow anaerobic fermentor under various operating conditions.

Finally, the feasibility of a continuation of this project will be reviewed. Any expansion or continuation of this project will continue to focus on the validity of considering low-cost reactor systems for the generation of biogas from animal manures and crop residues.