Methane Production from Dairy Cattle Waste

Spring 1981

Michael H. Scholla

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METHANE PRODUCTION FROM DAIRY CATTLE WASTE

BY

MICHAEL H. SCHOLLA
B.S., University of Central Florida, 1977

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science: Microbiology in the Graduate Studies Program of the College of Arts and Sciences at the University of Central Florida; Orlando, Florida

Spring Quarter
1981
ABSTRACT

Methane Production from Dairy Cattle Waste

A microbiological and economic study of methane production from dairy cattle waste was performed. The profit potential of producing methane and other vendable products from dairy cattle wastes was studied using a computerized cost model. The unit gas cost ($/cu. ft. methane) was determined for refractory volatile solids (VS) concentrations between 52% and 28% (W/W). Reaction rate constants (RKO) between $5.92 \times 10^9$ and $1.24 \times 10^{11}$ were used. Retention time (RT) was varied between 1 and 10 days. Total solids (TS) concentration was varied between 8% and 14%. Analyses were performed with and without a fertilizer plant option for upgrading digester effluent solids. Unit gas cost (UGC) decreased as RKO increased and as the refractory VS concentration decreased when determined without the fertilizer option. UGC decreased at short retention times as RKO increased when the fertilizer option was included. The unit gas costs were always above $8.00 per M. cu. ft. CH$_4$ without a fertilizer plant, and were consistently lower than the current intrastate market price of $3.18 per M. cu. ft. CH$_4$ when a fertilizer plant was incorporated into the system.

Microbiological studies were conducted using a multistage multistream digester. The design consisted of a 1,700 liter central digester with a working volume of 1,200 liters and 10, 50 liter satellite digesters with a working volume of 40 liters each.
The digester design allowed for the automatic addition of substrate to the central digester once per hour and three times per hour to the satellites. The digester was operated at 55°C and 10% TS with a 6 day RT in the central digester and 2 days RT in the satellites. Manure from a commercial dairy was utilized for substrate. Methane production was directly related to the type of cattle feed ration. It ranged between 1.27 and 0.3 liters CH$_4$ per liter of reactor fluid per day at a 6 day RT. Alkalinity, volatile fatty acids (VFA) and ammonia concentrations were related to methane production.

VFA concentrations were lower and methane production slightly higher in the satellite digesters. Analysis of the digester effluent for fertilizer value was investigated by drying for 10 days on a sand drying bed at an initial depth of 10 cm.

Total nitrogen, phosphorous (as P$_2$O$_5$) and potassium (as K$_2$O) concentrations were: 1.8%, 1.1% and 7.2% for undigested manure; 4.5%, 2.3%, and 9.1% for 6 day RT effluent; 2.0%, 1.1% and 7.5% for 8 day RT effluent.

Our economic studies indicate that digester operating conditions should include a 3-5 day RT, 10-12% TS, minimal changes in feed ration and recovery of solids for upgrading to fertilizer.
ACKNOWLEDGEMENT

I wish to express my sincere appreciation to all those who assisted in this research. To Dr. Rudy Wodzinski for his faith and guidance as my major professor. To Dr. R.N. Gennaro for his support and expertise in gas chromatography. To the Coordinating Council on the Restoration of the Kissimmee River-Nubbin Slough basin for funding. To my fellow "poop group" members Mary Galzerano, Sue Cox, and Doug Winkelmann. To my committee members Dr. Koevenig and Dr. Charba for their understanding. To the University of Central Florida Physical Plant, especially Dan Abbot and Pete Pilkington for their valuable assistance. To the faculty, staff and graduate students of the Department of Biological Sciences for surviving the odor. To S.K. Charba for her scientific and typing expertise. Finally, to my wife, Pamela, my Aunt Ellen, and the rest of my family without whose support and inspiration none of this would have been possible.
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LITERATURE REVIEW

Statement of problem in Okeechobee County, Florida. Okeechobee County, Florida, contains 32 dairies which house 26,600 milking cattle. The dairies are located in the Taylor Creek-Nubbin Slough basin which is part of the Lake Okeechobee watershed. The water table is very high in this area of Florida and flowing water covers the land much of the year. Typically, cattle stay in or near the water to remain cool. Their waste contributes a significant portion of the nutrient load in the runoff water entering Lake Okeechobee (5). Projections of the dairy cattle population indicate that the number of cattle in the area will increase (43).

One method that has been suggested for pollution abatement has been the anaerobic fermentation of dairy cattle waste to methane and other vendable products (43, 44). These products include carbon dioxide and fertilizer.

Anaerobic digestion would require the confinement of cattle to facilitate collection of their waste as would be necessary for any pollution abatement technique. Waste collection could be accomplished by water flushing or scraping. It would also be necessary to confine the cattle since they would be restricted from obtaining cover. Shading produces other economic benefits. Reduction of heat stress by providing shade has been reported to increase milk production and conception rates (9).
The anaerobic digestion of dairy cattle waste could significantly reduce the amount of nutrients entering Lake Okeechobee. Confinement and shading would increase milk production and conception rates. The products from the digestion process have an economic value which is sufficient to make the process economical (43, 44).

Economic impact of anaerobic digestion to methane and other vendable products. Estimates of the cost for producing methane by anaerobic fermentation vary widely. This variation is due to the type of digester used, data from which calculations are based, and estimation accounting practices used. There are benefits for which it is difficult to estimate costs. The esthetic value of cleaner waterways is one example. Most cost calculations mention these factors, but do not attempt to assign an economic value to them. Jewell et al. (18) reported that methane could be produced at $1.15 per thousand cubic feet (M. cu. ft.) for a 1,000-head, family-type dairy. This estimate included capital costs and operating costs. Credit was taken for energy. Smith et al. (31) reported that it would cost $0.12/kwh to produce electricity from methane for on site use. This estimation is based upon a mesophilic digester using beef cattle manure from 250 head as substrate. This estimation is also three times greater than the cost to buy power in the area. Hashimoto et al. (16) have reported a unit gas cost of $2.81/M. cu. ft. CH₄ for a 50,000 head beef cattle installation operating at thermophilic temperatures. When credit for a refeed value of the digester effluent was calculated, the unit gas cost was $2.47/M. cu. ft. CH₄. These estimations were based upon a 5700 liter pilot plant and recalculated to a 50,000 head installation. Coppinger
et al. (11) reported a unit gas cost of $2.36/M. cu. ft. CH$_4$ for a 400 head, mesophilic dairy digester. These calculations did not include labor costs since the system was located on a prison farm. Wodzinski et al. (43, 44) have reported a unit gas cost as low as -$3.25/M. cu. ft. CH$_4$ for a 60,000 head dairy installation. Process conditions were modeled after Varel et al. (41). Credits included energy, carbon dioxide, and fertilizer (digester solids upgraded to 6% N - 6% P - 6% K). Cost to confine cattle was not included due to the contention that the benefits realized from increased milk production and fertility rates enable the cost to be borne by the dairy operation.

The economic assessment of methane production is difficult because much of the data is obtained from small digesters and recalculated to large installations. The units used for reporting costs of producing methane are not consistent in the literature.

The process must be economically feasible if it is to be widely used for pollution abatement and energy production. Studies indicating the economic effect of research on the microbiology of methane production have not been reported.

**Microbiological aspects of methane production.** Methanogenic organisms are ubiquitous in areas containing high quantities of organic compounds and low amounts of oxygen. Various species of methanogenic bacteria have been detected in the rumen and gastrointestinal tract of animals, mud sediment, and soils covered by water in marine and freshwater environments (19, 20, 26, 34). Methanogens have also been isolated from the wetwood of trees (47), algal mats in hot springs (42), and the Florida aquifer (15). Studies on methane production in sediments
have contributed to the basic knowledge of methanogenesis which is applicable to any practical process.

R.S. Wolfe and his coworkers were responsible for the isolation of two biochemical components unique to methanogenic bacteria. Coenzyme M (CoM) was isolated by McBride and Wolfe (21). Identification of CoM as 2-mercaptoethanesulfonic acid and its chemical synthesis were achieved by Taylor and Wolfe (36). CoM is a methyl transfer enzyme and is required in all methanogens that have been studied (38, 39).

Cheeseman et al. (10) were responsible for the isolation of a low molecular weight, fluorescent compound, \( F_{420} \). \( F_{420} \) has not been identified, but it is present in all methanogenic bacteria examined. Studies demonstrate that \( F_{420} \) is required in hydrogen (39) and formate catabolism (35, 38) to methane. It has been suggested that the oxygen sensitivity of methanogens is due to \( F_{420} \) oxidation (30). This is based upon the observation that the enzymes are associated with \( F_{420} \) when reduced and disassociated when oxidized. The enzymes are stable when associated, but become labile upon disassociation.

The biochemical mechanisms for the formation of methane is depicted in Fig. 1. This model is the result of work performed primarily by Wolfe at the University of Illinois. Formate, carbon dioxide and hydrogen, acetate, and methanol can serve as substrates for methane production.

Most investigators believe that two phases exist in methane production. These are the non-methanogenic and the methanogenic phases. Bryant (8) has postulated that three phases exist. In the first phase, complex compounds are degraded to short chain fatty acids and alcohols.
Fig. 1. **Biochemical mechanism for the formation of methane.**
From (43).
FORMATE
NADP
NADPH₂
FORMIC DEHYDROGENASE
CO₂
H₂
CH₂O
H₂
CH₃OH
B₁₂**
METHYL TRANSFERASE
CO₂
B₁₂
ACETATE
F₄₂₀
FORMIC DEHYDROGENASE
H₂
CH₂O
H₂
CH₃OH
B₁₂**
METHYL TRANSFERASE
CH₃B₁₂
CO-M* FOLATE ENZYMES
HOOC-S-CoM
H₂
OHC-S-CoM
H₂
HOH₂C-S-CoM
H₂
CH₃-S-CoM
H₂
CH₄
Mg**, ATP
METHYL REDUCTASE
CH₄ + CoM

*COENZYME M
ACTIVE FORM: HSCH₂CH₂SO₃⁻

**CYANOCOBALAMIN
In the second or acetogenic phase, cells are produced and short chain fatty acids and alcohols are degraded to acetate, hydrogen and carbon dioxide. In the third or methanogenic phase, cells are also produced and methane is formed by oxidation of hydrogen and reduction of carbon dioxide. Other investigators combine the first two phases into the non-methanogenic phase.

The degradation of complex organic matter to methane precursors is performed by a variety of microorganisms (17). Dairy cattle waste contains many complex substrates which are dependent upon the feed ration (Table 1). Macromolecules in manure consist of polysaccharides (cellulose) (Fig. 2), oligosaccharides (hemicellulose) (Fig. 3), proteins (Fig. 4), lipids (Fig. 5), lignin (Fig. 6), nucleic acids and bacterial cell walls (Fig. 7). The degradation of these complex organic compounds are not catalyzed by a single microbial species. Populations of different organisms would have to exist in order to achieve demonstrated metabolic diversity. The macromolecules are degraded to monomers consisting of hexoses (Fig. 8), hexuronic acids (Fig. 3), amino acids (Fig. 4), fatty acids (Figs. 2-8), vanillin and vanillic acid (Fig. 6), nucleic acids, N-acetylglucosamine and N-acetylmuramic acid (Fig. 7). The monomers are further degraded by conventional pathways. Hexoses are degraded by the Embden-Meyerhof pathway (Figs. 2, 8). Hexuronic acids are oxidized and converted to pentoses which are degraded by the pentose pathway. Lipids are hydrolysed to glycerol and fatty acids. The acids are oxidized by beta fatty acid oxidation (Fig. 5). Aromatic compounds such as lignin are first hydroxylated followed by ring fission and beta fatty acid
Table 1. Composition of dairy cattle manure fed a high grain diet.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>%</th>
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<tr>
<td>Volatile solids</td>
<td>72.0</td>
</tr>
<tr>
<td>Ether extract</td>
<td>3.5</td>
</tr>
<tr>
<td>Cellulose</td>
<td>17.0</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>19.0</td>
</tr>
<tr>
<td>Lignin</td>
<td>6.8</td>
</tr>
<tr>
<td>Total N</td>
<td>3.0</td>
</tr>
<tr>
<td>Total N x 6.25 (Protein N)</td>
<td>19.0</td>
</tr>
<tr>
<td>Ammonia N</td>
<td>0.55</td>
</tr>
<tr>
<td>N on Ammonia Crude Protein</td>
<td>15.0</td>
</tr>
<tr>
<td>Volatile acid (as acetic)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

From (41).
Fig. 2. Biodegradation of cellulose to methane precursors. From (43).
Fig. 3. Biodegradation of xylans to methane precursors. From (43).
XYLANS
  ↓ C ENZYME
  ↓ Cx ENZYME
XYLOSE
  ↓ ISOMERASE
XYULOSE
  ↓ PENTOSE PATHWAY
  ↓ ACETATE
GLYCERALDEHYDE-3-PO₄
  ↓ EMBDEN MEYERHOF PATHWAY
PYRUVATE
  ↓ H₂
  ↓ CO₂
  ↓ ACETATE
  ↓ FORMATE
Fig. 4. Biodegradation of proteins and amino acids to methane precursors. From (43).
PROTEINS
  ↓ PROTEASES
PEPTIDES
  ↓ PEPTIDASES
AMINO ACIDS
  ↓ DEAMINATION
PHENYLALANINE
  ↓ HISTIDINE
TYROSINE
  ↓ GLUTAMATE
LYSINE
  ↓ ARGinine
LEUCINE
TRYPTOPHANE
ISOLEUCINE
METHIONINE
VALINE
  ↓ B-OXIDATION
ACETYLCOA
  ↓ ACETATE
FORMATE
PYRUVATE
ALANINE
THREONINE
GLYCINE
SERINE
CYSTEINE
CYSTINE
Fig. 5. **Biodegradation of lipids to methane precursors.**
From (43).
LIPIDS

GLYCEROL

EMBDEN MEYERHOFF PATHWAY

PYRUVATE

FATTY ACIDS

B-OXIDATION

CO₂ 

H₂ 

FORMATE 

ACETATE 

ACETATE
Fig. 6. Biodegradation of lignins to methane precursors. From (43).
LIGNINS

→ DEPOLMERIZATION

AROMATIC INTERMEDIATES

→ PHENOL OXIDASES

→ LACCASES

→ PEROXIDASES

→ VANILLIN, VANILLIC ACID, BENZOIC ACIDS, ETC.

→ RING FISSION

→ ORTHO

→ META

→ ACETATE

→ $\text{CH}_4 + \text{CO}_2$
Fig. 7. Biodegradation of bacterial cells to methane precursors. From (43).
Fig. 8. Biodegradation of disaccharides to methane precursors. From (43).
oxidation (Fig. 6). Amino acids are deaminated forming the corresponding fatty acid (Fig. 4).

The result of these reactions is the production of large amounts of direct precursors used for methane production (Fig. 9). These precursors are: acetate, formate, carbon dioxide, and hydrogen (46).

Anaerobic digesters contain a wide variety of microorganisms that catalyze these chemical reactions (17). The chemical species present in the digester must be in the proper proportion for efficient digestion (25). Changes in the substrate would undoubtedly result in changes of the microbial population.

Environmental factors affecting methane production. The limiting factors which effect methane production have been studied in the anaerobic digestion of sewage sludge. Physical factors which effect methane production include \( E_h \), pH, and temperature. The \( E_h \) must be lower than \(-200\) millivolts (6). The optimum has not been established. The pH range for methanogenesis is 6.5 to 8.6, with the optimum at 7.0 to 8.0 (17). The temperature range is from 20°C to 65°C, with the optimum for mesophilic digestion at 35°C. The optimum for thermophilic digestion is 60°C (41).

Ammonia concentrations greater than 200 mM are inhibitory in mesophilic systems regardless of pH. If ammonia concentrations are between 100 and 200 mM and the pH is greater than 7.4, the system is inhibited (41).

Alkalinity concentrations as high as 6000 mg CaCO\(_3\)/liter can be tolerated in mesophilic systems (18). Thermophilic systems will tolerate 7,700 mg CaCO\(_3\)/liter (41). The upper limit has not been esta-
Fig. 9. Interrelationship between the methane bacteria and other substances of the anaerobic carbon cycle. From (27).
CCTIPLEX SUBSTRATES (CARBOHYDRATE, LIPID, PROTEIN)

METHANOL → 2-PROPANOL → BUTANOL → ETHANOL → ACETATE

H₂ → BUTYRATE → ACETATE

GLYCEROL → SUCCHATE → LACTATE

FORMATE

CO₂

CH₄ + CO₂

CO₂

CH₄ + CO₂

CO₂

CH₄ + CO₂

CO₂

CH₄ + CO₂

CO₂

CH₄ + CO₂
blished in either system.

The effect of chemical factors on methane production has been extensively researched in sludge digesters. Stimulatory compounds and the investigators reporting them are listed in Table 2. Inhibitory compounds and the references are in Table 3.
### Table 2. Chemical factors which stimulate methane production or methanogens.

<table>
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<tr>
<th>Chemical factor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methylcobalamin</td>
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<tr>
<td>(Fe&lt;sup&gt;+++&lt;/sup&gt;) as FeCl&lt;sub&gt;3&lt;/sub&gt;</td>
<td>32</td>
</tr>
<tr>
<td>(Co&lt;sup&gt;++&lt;/sup&gt;) as CoCl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>32</td>
</tr>
<tr>
<td>(NH&lt;sub&gt;3&lt;/sub&gt;)</td>
<td>22</td>
</tr>
<tr>
<td>Rumen fluid growth factors</td>
<td>45</td>
</tr>
<tr>
<td>Acetate</td>
<td>45</td>
</tr>
<tr>
<td>B-vitamins</td>
<td>45</td>
</tr>
<tr>
<td>Folic acid</td>
<td>45</td>
</tr>
<tr>
<td>Coenzyme M (2-mercaptoethanesulfonate)</td>
<td>21</td>
</tr>
<tr>
<td>Soluble CHO</td>
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<tr>
<td>Branched chain fatty acids</td>
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</tr>
<tr>
<td>N-acetylglucosamine</td>
<td>28</td>
</tr>
<tr>
<td>Total acid</td>
<td>17</td>
</tr>
<tr>
<td>F420</td>
<td>24</td>
</tr>
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<td>Fatty acid concentrations</td>
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<td>Sulfate</td>
<td>24</td>
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<tr>
<td>Thiamine</td>
<td>32</td>
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<tr>
<td>Proline</td>
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</tr>
<tr>
<td>Glycine</td>
<td>32</td>
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<tr>
<td>Benzimidazole</td>
<td>32</td>
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*From (43).*
Table 3. Chemical factors which inhibit methane production or methanogens.

<table>
<thead>
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<th>Inhibitors</th>
<th>Reference</th>
</tr>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Heavy metals</td>
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</tr>
<tr>
<td>Cu++</td>
<td>23</td>
</tr>
<tr>
<td>Zn++</td>
<td>23</td>
</tr>
<tr>
<td>Ni+</td>
<td>23</td>
</tr>
<tr>
<td>Ag+</td>
<td>23</td>
</tr>
<tr>
<td>Hg++</td>
<td>23</td>
</tr>
<tr>
<td>Others</td>
<td>23</td>
</tr>
<tr>
<td>2. Methane analogs</td>
<td></td>
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<tr>
<td>CHCl₃</td>
<td>37</td>
</tr>
<tr>
<td>CCl₄</td>
<td>37</td>
</tr>
<tr>
<td>CH₂Cl₂</td>
<td>37</td>
</tr>
<tr>
<td>3. Others</td>
<td></td>
</tr>
<tr>
<td>Aminopterin</td>
<td>33</td>
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<td>Air</td>
<td>17</td>
</tr>
<tr>
<td>NO₃</td>
<td>17</td>
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<td>H₂</td>
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<tr>
<td>HCOOH</td>
<td>17</td>
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<tr>
<td>SO₄</td>
<td>46</td>
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</table>

From (43).
SECTION I: ECONOMIC ASSESSMENT OF METHANE PRODUCTION FROM DAIRY CATTLE WASTE

The economic impact of decreasing the refractory volatile solids concentration and increasing the reaction rate constant was examined with a computerized cost model. The unit gas cost (UGC) ($/M. cu. ft. CH₄) was determined for refractory volatile solids concentrations between 28% and 52% (W/W). Reaction rate constants ranging from $5.92 \times 10^9$ to $1.24 \times 10^{11}$ were applied to the model. Analyses were performed at 55°C. Retention time was varied between 1 and 10 days. Total solids concentration was varied between 8% and 14% (W/W). All analyses were performed with and without a fertilizer plant option for upgrading digester effluent solids. Unit gas cost (UGC) without a fertilizer plant decreased as the refractory volatile solids concentration decreased. UGC also decreased as the reaction rate constant increased. UGC increased as volatile solids concentration decreased with a fertilizer plant. UGC decreased as the reaction rate constant increased at short retention times with fertilizer plant. Unit gas costs were always above $8.00 per M. cu. ft. methane without a fertilizer plant, and were consistently lower than the current market price of $3.18 per M. cu. ft. methane when a fertilizer plant was incorporated into the system.
INTRODUCTION

Anaerobic digestion of dairy cattle waste to methane and fertilizer reduces the biochemical oxygen demand (BOD) of the manure, although the concentrations of nitrogen, phosphorous, and potassium are not significantly reduced. The process has the potential to be used to abate pollution caused by dairy cattle manure. The residual nitrogen, phosphorous and potassium (NPK) have economic value as fertilizer. The sale of methane and carbon dioxide also contribute to the profit potential. If it is economical to recover these products, the process can be used to reduce the BOD and NPK entering the environment.

Okeechobee County, Florida, is an area where the anaerobic digestion of dairy cattle waste could be used to abate pollution. Thirty-two dairies are located in the Taylor Creek-Nubbin Slough Basin in Okeechobee County (Fig. 10). The basin is part of the Lake Okeechobee watershed. The water table is high in this area of Florida and the land is covered by flowing water much of the year. Typically, cattle stay in or near the water to stay cool. Their waste contributes a significant portion of the nutrient load in the runoff water entering Lake Okeechobee (5). According to the Dairy Summary printed by the Florida Crop and Livestock Reporting Service (12), 32 dairies in the area housed approximately 62,200 dairy cattle in 1978. The human population was estimated to be 19,800 in 1978. The rate of growth of the dairy cattle population in Okeechobee is estimated to be
Fig. 10. Location of dairy herds in Taylor Creek-Nubbin Slough Basin. (Letter designations correspond to dairies listed in Table 4.)
Table 4. Number of dairy cattle in Taylor Creek-Nubbin Slough Basin and adjacent areas in 1978.

<table>
<thead>
<tr>
<th>Code</th>
<th>Dairy</th>
<th>Milkers</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Boyd</td>
<td>250</td>
<td>312 est.</td>
</tr>
<tr>
<td>B</td>
<td>Boynton Beach</td>
<td>450</td>
<td>600</td>
</tr>
<tr>
<td>C</td>
<td>Davie</td>
<td>600</td>
<td>750</td>
</tr>
<tr>
<td>D</td>
<td>Dry Lake</td>
<td>1,000</td>
<td>1,660</td>
</tr>
<tr>
<td>E</td>
<td>Enrico</td>
<td>1,400</td>
<td>2,000</td>
</tr>
<tr>
<td>F</td>
<td>F &amp; R</td>
<td>728</td>
<td>970</td>
</tr>
<tr>
<td>G</td>
<td>Flying G</td>
<td>980</td>
<td>1,200</td>
</tr>
<tr>
<td>H</td>
<td>Larson #1</td>
<td>1,200</td>
<td>1,550</td>
</tr>
<tr>
<td>I</td>
<td>Larson #3</td>
<td>1,300</td>
<td>1,600</td>
</tr>
<tr>
<td>J</td>
<td>New BB McArthur</td>
<td>1,500</td>
<td>1,875 est.</td>
</tr>
<tr>
<td>K</td>
<td>Charles McArthur 1</td>
<td>1,500</td>
<td>1,700</td>
</tr>
<tr>
<td>L</td>
<td>Charles McArthur 2</td>
<td>1,460</td>
<td>1,825 est.</td>
</tr>
<tr>
<td>M</td>
<td>Charles McArthur 3</td>
<td>1,500</td>
<td>1,875 est.</td>
</tr>
<tr>
<td>N</td>
<td>Charles McArthur 4</td>
<td>1,500</td>
<td>1,175 est.</td>
</tr>
<tr>
<td>O</td>
<td>McArthur Inc. 1</td>
<td>1,000</td>
<td>1,125 est.</td>
</tr>
<tr>
<td>P</td>
<td>McArthur Inc. 2</td>
<td>1,000</td>
<td>1,300</td>
</tr>
<tr>
<td>Q</td>
<td>McArthur Inc. 3</td>
<td>1,000</td>
<td>1,125 est.</td>
</tr>
<tr>
<td>R</td>
<td>McArthur Inc. 7</td>
<td>1,000</td>
<td>1,125 est.</td>
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<tr>
<td>S</td>
<td>McArthur Inc. 8</td>
<td>1,000</td>
<td>1,300</td>
</tr>
<tr>
<td>T</td>
<td>L.N. McArthur</td>
<td>1,500</td>
<td>500</td>
</tr>
<tr>
<td>U</td>
<td>Murphy White</td>
<td>800</td>
<td>1,000</td>
</tr>
<tr>
<td>V</td>
<td>Newcomer</td>
<td>550</td>
<td>750</td>
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<tr>
<td>W</td>
<td>Paler</td>
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<td>375 est.</td>
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<tr>
<td>X</td>
<td>Posey</td>
<td>465</td>
<td>581 est.</td>
</tr>
<tr>
<td>Y</td>
<td>Ret Top #4</td>
<td>560</td>
<td>750</td>
</tr>
<tr>
<td>Z</td>
<td>E &amp; S Rucks</td>
<td>800</td>
<td>1,060</td>
</tr>
<tr>
<td>AA</td>
<td>H &amp; T Rucks</td>
<td>700</td>
<td>875 est.</td>
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<tr>
<td>BB</td>
<td>Vernon Rucks</td>
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<td>800</td>
</tr>
<tr>
<td>CC</td>
<td>Wilson Rucks</td>
<td>550</td>
<td>750</td>
</tr>
<tr>
<td>DD</td>
<td>Sez</td>
<td>620</td>
<td>775 est.</td>
</tr>
<tr>
<td>EE</td>
<td>Williams &amp; Son</td>
<td>325</td>
<td>406 est.</td>
</tr>
<tr>
<td>FF</td>
<td>Wloof</td>
<td>400</td>
<td>500 est.</td>
</tr>
</tbody>
</table>

**TOTAL** 28,538 34,189 est.

*Code refers to the location of the dairies in Fig. 10.*
3,900 cattle per year (Table 5). The rate of growth of the human population is estimated to be 900 people per year (Table 6). If the present rate of growth continues, 37% of the dairy cattle in Florida would be located in Okeechobee County by the year 2000. It is unlikely that this will occur due to land limitations and the continuance of urban expansion. However, the number of dairy cattle in the area will increase. There is a discrepancy between the data presented in the Dairy Summary and an actual census made by the Coordinating Council on the Restoration of the Kissimmee River-Nubbin Slough Basin (a State agency). The Coordinating Council staff estimate of 26,600 milkers was used for the economic analysis reported in this study and in the computer modeling analysis performed by Wodzinski et al. (43, 44).

The potential for recovery of resources from cattle waste can be profitable in Okeechobee County if credits are realized from additional resources contained in the digester effluent (43, 44). Credits for fertilizer and carbon dioxide can be realized if the facility is of sufficient size.

Any manure digestion process would require the effective collection of the manure. The only feasible method is to confine the cattle. Such an installation would require a mechanical method of manure collection such as flushing with water or removal by scraping. It would also be necessary to shade the cattle since they would be restricted from seeking cover. This produces other economic benefits. Reduction of heat stress by providing shade has been reported to increase milk production and conception rates (9). Therefore, it is contended that the cost of cattle confinement should not be borne solely by the
Table 5. Estimates of dairy cattle population in the State of Florida and Okeechobee County.

<table>
<thead>
<tr>
<th>Date</th>
<th>State</th>
<th>Okeechobee County</th>
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</thead>
<tbody>
<tr>
<td>1/1/70</td>
<td>238.5</td>
<td>30.0</td>
</tr>
<tr>
<td>1/1/71</td>
<td>242.8</td>
<td>N.A.</td>
</tr>
<tr>
<td>1/1/72</td>
<td>246.2</td>
<td>39.3</td>
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<tr>
<td>1/1/73</td>
<td>248.7</td>
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<td>1/1/74</td>
<td>258.1</td>
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<td>1/1/75</td>
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<td>1/1/76</td>
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<td>53.6</td>
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<td>1/1/78*</td>
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<td>62.2</td>
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<tr>
<td>1/1/80*</td>
<td>290.1</td>
<td>70.0</td>
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<tr>
<td>1/1/85*</td>
<td>316.7</td>
<td>89.7</td>
</tr>
<tr>
<td>1/1/90*</td>
<td>343.4</td>
<td>109.3</td>
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<tr>
<td>1/1/00*</td>
<td>396.6</td>
<td>148.6</td>
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*Estimate of population based on data for years 1970-76, from (12).
Table 6. Estimates of human population in the State of Florida and Okeechobee County.

<table>
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<tr>
<th>Date</th>
<th>State</th>
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<td>4/1/65</td>
<td>5,961.6</td>
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<td>4/1/70*</td>
<td>6,791.4</td>
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<tr>
<td>7/1/71</td>
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<td>7/1/72</td>
<td>7,441.5</td>
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<td>7,845.1</td>
<td>14.7</td>
</tr>
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<td>7/1/74</td>
<td>8,248.9</td>
<td>16.3</td>
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<td>7/1/75</td>
<td>8,485.2</td>
<td>17.0</td>
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<td>7/1/76</td>
<td>8,551.8</td>
<td>17.9</td>
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<td>7/1/78</td>
<td>8,908.0</td>
<td>19.8</td>
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<td>10,538.0</td>
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<tr>
<td>7/1/00</td>
<td>13,572.0</td>
<td>36.2</td>
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*Census data for 1970 from (40). All other data from (13).
Fig. 11. The rate of growth and the projected rate of growth of the human population in Florida and the rate of growth and projected rate of growth of dairy cattle in Florida. Correlation coefficients refer to the line of best fit. Correlation coefficients for human and dairy cattle populations equal 0.996 and 0.970. Symbols: (●) human population; (★) dairy cattle population. From (12).
digestion process.

The purpose of this study is to examine the effects of possible improvements to the bioconversion process on the profitability of resource recovery. These improvements include the reduction of the refractory volatile solids concentration and increasing the bioconversion rate.
MATERIALS AND METHODS

Computerized cost model. The computerized cost model developed by Ashare et al. (3) at Dynatech and modified by Wodzinski et al. (43, 44) at the University of Central Florida was used. The model utilized capital cost data supplied by Hamilton Standard and other equipment suppliers (43). The Hamilton Standard data were actual costs incurred at the digester facility at Kaplan Industries in Bartow, Florida. This model is accurate for relatively large installations.

The cost model calculations are reflected in the unit gas cost (UGC). The UGC is the cost, in dollars, to produce 1,000 cu. ft. of methane. This pricing structure is typically used in the petroleum industry.

The cost model offers several options to the user and includes: (1) type of digester; (2) gas usage; (3) centrifuge usage; (4) heat exchanger usage; (5) digester design; (6) electricity credits; (7) cattle confinement costs; (8) effluent solids credits; (9) type of fertilizer plant; (10) type of nitrogen used in fertilizer plant.

The operator also has the option to request either a complete listing of the process conditions, calculation of total plant investment, manufacturing costs, unit gas cost, and pollution abatement impact (Appendix I) or a brute force iteration (Appendix II). The brute force iteration is a method used to calculate the unit gas cost while varying temperature, total solids concentration, and retention time in operator-
controlled increments.

Extensive documentation of the logic flow, available options, process conditions and capital cost information is available elsewhere (3, 43). A listing of the computer program is in Appendix III. Variable names and their units are in Appendix IV. Data input format is in Appendix V.

**Analysis of factors influencing gas production.** Gas production was calculated by the equation:

\[(1) \quad GT = 0.37*A*(SO-S1)*RNUM/HRT\]

where

- \(GT\) = Gas production in L gas/L reactor/day
- \(A\) = COD to biodegradable influent solids
- \(SO\) = Volatile solids concentration in influent (g/L)
- \(S1\) = Volatile solids concentration in effluent (g/L)
- \(RNUM\) = Number of digesters
- \(HRT\) = Hydraulic retention time (days)

All of the above values except \(S1\) were provided in the data input either as one value or as several values using the brute force iteration.

\(S1\) was calculated by the equation:

\[(2) \quad S1 = ((1-R)*SO/(((HRT*RK/RNUM)+1)**RNUM)+R*SO)\]

where

- \(RK\) = First order reaction rate constant (days \(^{-1}\))
- \(R\) = Fraction of refractory volatile solids

\(RK\) was calculated by the equation:

\[(3) \quad RK = RKO*EXP(E/(T+273))\]

where

- \(RKO\) = Constant in Arrhenius rate expression
- \(E\) = Arrhenius activation energy divided by gas constant
- \(T\) = Temperature
Gas production was dependent upon the amount of volatile solids converted. In order to increase gas production, the concentration of volatile solids in the effluent (Sl) would have to be decreased. For any given temperature, retention time and volatile solids influent concentration (S0), Sl can be decreased by decreasing the refractory volatile solids concentration (R) and/or increasing the Arrhenius rate constant RKO. In this study, R was varied between 28% and 52%. RKO was varied between $5.92 \times 10^9$ and $1.24 \times 10^{11}$. The analysis was performed using the brute force iteration. The temperature was maintained at 55°C. Total solids concentration in the influent was varied from 8 - 14% (W/W). Retention time was varied from 1 - 10 days. Modification of the output from the iteration was performed. Sl and the percent volatile solids conversion (VSCON) were requested instead of the heat requirements and makeup water requirements. The analysis was performed with and without the fertilizer plant option. Data input parameters are listed in Appendix IV.
RESULTS

Effect of retention time on volatile solids conversion and annual gas production. The percent volatile solids conversion and annual gas production increased as retention time increased (Figs. 12, 13). The rate of increase was greater at shorter retention times than at longer retention times.

Effect of total solids concentration on unit gas cost. Unit gas cost decreased as total solids concentration increased (Fig. 14).

Effect of refractory volatile solids concentration on percent volatile solids conversion and gas production. The percent volatile solids and total gas production increased as refractory volatile solids concentration decreased (Figs. 15, 16). Volatile solids conversion was 16.7% when the refractory volatile solids concentration was 52% at a one day retention time. The percent conversion was highest when the retention time was 10 days and the refractory volatile solids were 28%. This condition resulted in 60.6% volatile solids conversion. Gas production was lowest and highest under these two conditions. The first condition resulted in $9.357 \times 10^4$ M cu. ft. methane/year, and the second resulted in $3.433 \times 10^5$ M cu. ft. methane/year.

Effect of reaction rate constant on percent volatile solids conversion and gas production. Percent volatile solids conversion and gas production increased as the reaction rate constant (RKO) increased (Figs. 17, 18). The lowest values for conversion and gas production
Fig. 12. Effect of retention time on percent volatile solids conversion. Symbols: (●) $R = 52.4$, $RKO = 5.92 \times 10^9$. 
(\% W/W) VS CONVERSION
Fig. 13. Effect of retention time on annual gas production. Symbols: (●) $R = 52.4$, $RK0 = 5.92 \times 10^9$. 
Fig. 14. Effect of total solids concentration on unit gas cost. Symbols: (●) HRT = 1; (■) HRT = 3.
Fig. 15. Effect of refractory volatile solids concentration on percent volatile solids conversion. Symbols: (●) \( R = 28\% \); (■) \( R = 33\% \); (▲) \( R = 38\% \); (○) \( R = 43\% \); (□) \( R = 48\% \); (△) \( R = 52\% \).
Fig. 16. Effect of refractory volatile solids concentration on annual gas production. Symbols: (●) $R = 28\%$; (■) $R = 33\%$; (▲) $R = 38\%$; (○) $R = 43\%$; (□) $R = 48\%$; (△) $R = 52\%$. 
Fig. 17. Effect of reaction rate constant on percent volatile solids conversion. Symbols: (●) $RKO = 1.24 \times 10^{11}$; (▲) $RKO = 6.51 \times 10^{10}$; (■) $RKO = 3.55 \times 10^{10}$; (○) $RKO = 1.78 \times 10^{10}$; (△) $RKO = 1.48 \times 10^{10}$; (□) $RKO = 1.18 \times 10^{10}$; (●—●) $RKO = 8.88 \times 10^9$; (▲—▲) $RKO = 5.92 \times 10^9$. 
Fig. 18. Effect of reaction rate constant on annual gas production. Symbols: (●) RKO = 1.24 x 10^{11}; (■) RKO = 6.51 x 10^{10}; (▲) RKO = 1.78 x 10^{10}; (○) RKO = 8.88 x 10^{9}; (□) RKO = 5.92 x 10^{9}. 
were obtained at a 1 day retention time with RKO equal to $5.92 \times 10^9$.

Those values were 16.7% and $9.436 \times 10^4$ M. cu. ft. methane per year.

Highest values of 47.6% and $2.695 \times 10^5$ M. cu. ft. methane per year were obtained on a 10 day retention time when $RKO = 1.24 \times 10^{11}$.

**Effect of refractory volatile solids concentration on unit gas cost without a fertilizer plant.** The unit gas cost decreased as the refractory volatile solids concentration decreased (Fig. 19). The highest unit gas cost was $32.75$ per M. cu. ft. methane at 52% refractory volatile solids, a 1 day retention time, and 8.0% total solids. The lowest unit gas cost was $9.74$ per M. cu. ft. methane at 28% refractory volatile solids, a 10 day retention time, and 14% total solids. Unit gas cost increased as total solids decreased.

**Effect of refractory volatile solids concentration on unit gas cost with a fertilizer plant.** Unit gas cost decreased as refractory volatile solids concentration decreased (Fig. 20). The unit gas cost does not, however, continue to decline with increased retention time when the refractory volatile solids concentration is greater than 33% at 10% total solids. Unit gas cost does decrease as influent total solids increase. The highest unit gas cost was $9.23$ per M. cu. ft. methane at 8% total solids, a 1 day retention time, and 28% refractory volatile solids. The lowest unit gas cost was $1.58$ per M. cu. ft. methane at 14% total solids, a 4 day retention time, and 52% refractory volatile solids. The lowest unit gas cost at 10% total solids and 52% refractory volatile solids was at a 4 day retention time. The unit gas cost was $1.96$. However, the unit gas cost at 3 and 5 day retention times were $1.97$ and $1.98$ respectively. The
Fig. 19. Effect of refractory volatile solids concentration on unit gas cost without a fertilizer plant. Symbols: (●) R = 28%; (■) R = 33%; (▲) R = 38%; (○) R = 43%; (□) R = 48%; (△) R = 52%.
Fig. 20. Effect of refractory volatile solids concentration on unit gas cost with a fertilizer plant. Symbols: (●) R = 28%; (■) R = 33%; (▲) R = 38%; (○) R = 43%; (□) R = 48%; (△) R = 52%.
lowest unit gas costs at 48% refractory volatile solids and 10% total solids were at 4 to 7 day retention times with costs of $2.68, $2.64, $2.65 and $2.67 respectively.

Effect of reaction rate constant on unit gas cost without a fertilizer plant. Unit gas cost decreased as the reaction rate constant (RKO) increased (Fig. 21). The unit gas cost did not continue to decline with retention time when the reaction rate constant was greater than $1.78 \times 10^{10}$ at 10% total solids and a refractory volatile solids concentration of 52%. The highest UGC was $32.75$ per M. cu. ft. methane at 8.0% total solids, a 1 day retention time and when the reaction rate constant was $5.92 \times 10^9$. The lowest UGC of $12.06$ occurred at 13% total solids, a 3 day retention time and when RKO was $1.24 \times 10^{11}$. The lowest UGC at 10% total solids was $12.22$ when the retention time was three days and RKO was $1.24 \times 10^{11}$. When the retention time was four and five days, the UGC was $12.25$ and $12.30$ respectively.

Effect of reaction rate constant on unit gas cost with a fertilizer plant. Unit gas cost decreased as the reaction rate constant (RKO) increased (Fig. 22). The UGC did not continue to decrease with retention time. When RKO was equal to $5.92 \times 10^9$, the UGC decreased to $1.96$ at a 4 day retention time. After four days, the UGC increased. The point of inflection occurred at shorter retention times as RKO was increased. The highest unit gas cost of $2.88$ occurred when RKO was equal to $5.92 \times 10^9$, the retention time was 1 day and the total solids concentration was 8%. The lowest unit gas cost was $0.90$ at a 1 day retention time, 14% total solids and when RKO was equal to $1.24 \times 10^{11}$. 
Fig. 21. Effect of reaction rate constant on unit gas cost without a fertilizer plant. Symbols: (●) RKO = 1.24 \times 10^{18}; (▲) RKO = 6.51 \times 10^{16}; (■) RKO = 3.55 \times 10^{16}; (○) RKO = 1.78 \times 10^{10}; (△) RKO = 1.48 \times 10^{10}; (□) RKO = 1.18 \times 10^{9}; (●--●) RKO = 8.88 \times 10^7; (▲--▲) RKO = 5.92 \times 10^7.
Fig. 22. Effect of reaction rate constant on unit gas cost with a fertilizer plant. Symbols: (●) RKO = \(1.24 \times 10^{14}\); (▲) RKO = \(6.51 \times 10^{10}\); (■) RKO = \(3.55 \times 10^{10}\); (○) RKO = \(1.78 \times 10^{10}\); (△) RKO = \(1.48 \times 10^{10}\); (□) RKO = \(1.18 \times 10^{10}\); (●—●) RKO = \(8.88 \times 10^9\); (∆—∆) RKO = \(5.92 \times 10^9\).
Effect of refractory volatile solids concentration and reaction rate constant on unit gas cost without a fertilizer plant. Unit gas cost decreased as refractory volatile solids decreased and as the reaction rate constant increased (Fig. 23). The greatest effect on decreasing the unit gas cost was the concentration of refractory volatile solids. However, the unit gas cost was never below $8.00 per M. cu. ft. methane.

Effect of refractory volatile solids concentration and reaction rate constant on unit gas cost with a fertilizer plant. Unit gas cost decreased as the refractory volatile solids concentration and the reaction rate constant increased (Fig. 24). The greatest effect on decreasing the unit gas cost was increasing the concentration of refractory volatile solids. The unit gas costs were consistently lower than $4.00 per M. cu. ft. The unit gas costs were lower than $2.15 when the refractory volatile solids concentration was 52%.
Fig. 23. Effect of refractory volatile solids concentration and reaction rate constant on unit gas cost without a fertilizer plant. Symbols: (△--△), RKO = 5.92 x 10⁻⁹, R = 52%; (●--●), RKO = 5.92 x 10⁻⁹, R = 28%; (△--△), RKO = 1.24 x 10⁻¹, R = 52%; (○--○), RKO = 1.24 x 10⁻¹, R = 28%.
Fig. 24. Effect of refractory volatile solids concentration and reaction rate constant on unit gas cost with a fertilizer plant. Symbols: (●) R = 28%; (■) R = 33%; (▲) R = 38%; (○) R = 43%; (□) R = 48%; (△) R = 52%; (——) RKO = $5.92 \times 10^9$; (----) RKO = $1.24 \times 10^{11}$. 
DISCUSSION

The effect of refractory volatile solids concentration and reaction rate constant on the economics of bioconversion of dairy waste were studied. The refractory volatile solids concentrations were varied between 28% and 52%. Varel et al. (41) reported that 52.4% of the volatile solids in dairy manure are refractory. Analysis of dairy cattle manure has shown that lignin comprises 28% of the volatile solids (41). It is unlikely that any significant portion of the lignin would be degraded within 10 days at 55°C. This information was used to determine the parameters of this study.

The reaction rate constant was varied between $5.92 \times 10^9$ and $1.24 \times 10^{11}$. The value of $5.92 \times 10^9$ was determined by Ashare et al. (3) through a least square fit of experimental data obtained by several investigators. This was the minimum attainable rate. The higher values that were used were estimates of potential increases in rate that might be obtained if the fermentation was optimized by strain selection, physical and chemical parameters, and nutritional techniques. Aerobic fermentations have been optimized by a combination of these techniques. Rates of fermentation and increases in total yields of desired products are commonplace. The values used were 1.5, 2.0, 2.5, 3.0, 6.0, 11.0, and 20.9 times the rate calculated by Ashare.

Higher yields of methane should be produced by a digestion process that degrades a higher proportion of the volatile solids in the feed.
material. Yields might also be increased by a digestion system that contained organisms that would convert the volatile solids to methane at a faster rate.

Wodzinski et al. (43, 44) have determined that this process is economical if the solids are recovered from the digester effluent and upgraded to a 6-6-6 fertilizer before sale. Without this type of solids recovery, the process is uneconomical at any of the reaction rate constants and refractory volatile solids concentrations studied. The lowest unit gas cost without a fertilizer plant reported in this study was more than $8.00 per M. cu. ft. methane. The price of methane is presently $3.18 per M. cu. ft. Premex, the natural gas cartel in Mexico, commands a price of $4.62 per M. cu. ft. methane. The unit gas cost was lower than these figures when the fertilizer plant was included in the calculations.

At the present digestion conditions of 52% refractory volatile solids and a reaction rate constant of $5.92 \times 10^9$, the unit gas cost with a fertilizer plant was $1.98 per M. cu. ft. methane at a 5 day retention time. Hashimoto et al. (16) have reported a unit gas cost of $2.81 per M. cu. ft. methane for an installation of 50,000 head of beef cattle. These calculations did not utilize credits for carbon dioxide production. The above does not reflect a credit for refeeding of solids. The unit gas cost was calculated at $2.47 per M. cu. ft. methane when a credit of $60.96/ton was realized from refeed of solids. The refeed credit does not require an upgrading cost before its sale. The only cost necessary is a recovery cost. This is also necessary in fertilizer production. The cost of recovery of the solids for fertil-
izer may be less than the cost of solids for refeed. Hashimoto's costs were based upon results obtained with a 5,700 liter pilot plant digester and recalculated to a 50,000 head installation.

Decreasing the refractory volatile solids concentration increases methane production, but it also increases the unit gas cost if a fertilizer plant is used. The solids have a greater value in their present form than as methane. The unit gas cost can be reduced by increasing the reaction rate. This will increase the amount of methane produced and will decrease the required digester volume. A lower volume will result in a lower capital cost expenditure. The decreases in unit gas cost that result from an increased rate are attractive from an economic standpoint. At the present reaction rate of $5.92 \times 10^9$, the process is economical. Any increase in rate will result in additional profits for the operator of such a system.

The digestion process should be optimized for maximum methane production, in the shortest time, with minimum solids degradation. Further experimentation is needed to determine the minimum digestion time for stabilization of the dairy waste solids and removal of substances that are toxic to plants, if any. Further study is also needed to determine the advantages of fertilizer with a highly organic base and low leachability such as dairy cattle waste. The effect of digested wastes on upgrading poor soils such as those found in much of Florida should be examined. Not only could this result in increased crop acreage, but it might also allow the product to command a higher price than inorganic fertilizer.
The anaerobic digestion of dairy cattle waste to methane was investigated using a multistage multistream digester. The digester design consisted of a 1,700 liter central digester with a working volume of 1,200 liters and 10, 50-liter satellite digesters with working volumes of 40 liters each. This design allowed for the automatic addition of substrate to the central and satellite digesters, once and three times per h respectively. The digester was operated at 55°C and 10% total solids (TS), with a 6 day retention time (RT) in the central digester and a 2 day RT in the satellites. This resulted in a total RT of 8 days. Manure from a commercial dairy was used as substrate. Methane production was directly related to changes in cattle feed ration and ranged between 1.27 and 0.3 liters methane per liter of reactor fluid per day at a 6 day RT. Alkalinity, volatile fatty acid (VFA) and ammonia concentrations were related to methane production. VFA concentrations were lower and methane production slightly higher in the satellite digesters. Variability between satellite digesters was minimal on any given day. Digester effluent was analyzed for fertilizer value after drying for 10 days on a sand drying bed at an initial depth of 10.0 cm. Total N, P₂O₅, and K₂O concentrations were 1.8%, 1.1%, and 7.5% for undigested manure; 4.5%, 2.3%, and 9.1% for 6 day RT effluent; and 2.0%, 1.1%, and 7.5% for 8 day RT effluent. These studies
indicate that a 3-5 day RT at 10-12% TS with minimal changes in cattle feed ration and recovery of solids for fertilizer usage will result in a stable and economical digestion system.
INTRODUCTION

The anaerobic digestion of dairy cattle waste reduces the biochemical oxygen demand of the manure. This aids in the abatement of water pollution. If the process is to be widely accepted, it must be economical. Studies indicate that the process can be economical if the saleable end products of the fermentation are recovered \((43, 44)\). These products are methane, carbon dioxide, nitrogen, phosphorous and potassium.

The production of methane at thermophilic temperatures results in high rates of digestion. Thermophilic digestion would also theoretically minimize the survival of bacterial pathogens. Most of the research that has been conducted utilizes 3 to 10 liter digesters in which carefully controlled substrate is introduced once or twice per day \((29, 41)\). On a large scale, methane fermentations would probably be conducted on a continuous feed basis. This study was initiated to design and construct a laboratory scale digester system which approached continuous fermentation conditions. Substrate for the digester was from a commercial dairy in which the investigators had no control over the cattle feed ration. The study also investigated the total nitrogen, phosphorous \(\text{as P}_2\text{O}_5\), and potassium \(\text{as K}_2\text{O}\) concentrations present in the digester effluent and its components.
MATERIALS AND METHODS

Reactors. A multistage, multistream digester was designed, constructed and used in this study. The design consisted of a 1,700 liter digester which had a working volume of 1,200 liters and 10 50-liter satellite digesters with working volumes of 40 liters each (Fig. 25).

Manure was diluted to the desired concentration and ground with a submersible grinder pump (Peabody Barnes, Model 203) mounted in a 208 L plastic lined drum (Fig. 26). The diluted manure was then transferred to another 208 liter drum which served as the central digester feed reservoir. This was equipped with a mixing pump (Teel, 1P795) (Fig. 27). The mixing pump was controlled by a microprocessor (Micromaster, Model WP-6001). Manure was introduced to the central digester with an air actuated diaphragm pump (Wilden, Model M4). Flow rate was controlled by a pressure regulator with a gauge (Wilkerson, Model R-20-02-000 and GRP-49-038). The quantity of manure delivered to the central digester was controlled by a microprocessor and solenoid (Skinner, Model 247). The central digester was fed every hour. The central digester consisted of a 2.29 m x 2.29 m polyvinylchloride (PVC)-coated nylon bag with influent, effluent and eight sample ports (Fig. 28). All ports were 2.45 cm I.D. PVC pipe. Penetration of the bag was through standard water bed fittings which were glued and clamped to the pipe. Influent and effluent ports extended to the bottom of the digester. The central digester was in a 2.7 m x 3.35 m 60°C walk-in
Fig. 25. Multistage, multistream semi-continuous digester design.
Manure Recirculating and Feed Loop

- Gas Removal System
- Central Digester Feed Line
- Satellite Digester Feed Valves
- Incubator Wall
- Satellite Digesters
- Sample and Control Ports
- Central Digester (Pliable)
Fig. 26. *Manure grinder pump.*
Fig. 27. Central digester substrate reservoir and addition pump.
Fig. 28. Central and satellite digesters.
incubator with its controls located on the exterior (Fig. 29).

The contents of the central digester were mixed by pumping manure from the bag, through the recirculation loop and back into the bag. The manure was pumped by an air actuated diaphragm pump. Pressure fluctuations within the recirculation pipe were controlled by a surge suppressor (Blacacoli, Model Sentry 1) while the pumping rate was controlled by a pressure regulator (Fig. 30).

Manure from the central digester was fed at specified rates to each of 10 identical satellite digesters (Figs. 28, 31). The body of each satellite digester was a 50 liter autoclavable polypropylene carboy. The carboy was attached to a mixing pump (Teel, Model 1P795) with a 2.54 cm I.D. PVC pipe. Penetration of the carboy body was made with a 2.54 cm I.D. male threaded coupling. This connection was sealed with a rubber washer and clear silicon caulking. The mixing pump was regulated by a one-hour cycle time (Dayton, Model 2E357). Manure was introduced to the digester with a 2.54 cm I.D. air actuated valve equipped with a butyl rubber sleeve (Red Valve Co., Series 2600), which was connected to the central digester recirculating loop. Air pressure to the valve was controlled with a pressure regulator. Activation of the valve was controlled by a microprocessor and a solenoid (Asco, Model 8320A172) (Fig. 32).

Digested manure was removed from the carboy via an overflow system. Gas produced in the satellite and central digesters was removed through a gas removal system consisting of 5.08 cm I.D. PVC pipe with a fan on one end. This resulted in a slight negative pressure within the satellite digesters which enabled the effluent overflow
Fig. 29. *Digester support apparatus.*
Fig. 30. **Digester controls, recirculatory pump and surge suppressor.**
Fig. 31. Satellite digester.
Fig. 32. Digester controls: air solenoids and microprocessors.
system to operate.

**Process conditions.** The following process conditions were utilized in this study: temperature, 55°C; total solids, 10% (W/W); central digester retention time, 6 days; satellite digester retention time, 2 days. Substrate was added to the central digester once per hour while satellite digesters were charged with substrate three times per hour. Mixing was for 5 minutes at 20 minute intervals in the satellite digesters. The central digester was mixed continuously. Mixing was for four minutes in the manure reservoir prior to the central digester substrate addition.

**Substrate.** Dairy waste (feces and urine) was collected from a commercial dairy near Orlando, Florida, from May to August, 1980. The collection site was a feed area with a concrete floor and aluminum roof. Milkers and dry cattle were fed within the sample area. The number of milkers and dry cattle in the collection area varied as did the feed ration (Table 7). Milkers were fed twice per day, whereas dry cattle were fed once daily. Waste accumulated for two to five days before the area was cleaned. The waste was shoveled into 208 liter plastic lined steel barrels and transported to the laboratory at ambient temperature. The waste was stored at 4°C and used within 10 days. The total solids (TS) concentration varied between 17.2 and 21.5% (W/W); volatile solids (VS) concentration varied between 67.5 and 81.0% (W/W) (Table 8). The waste was diluted to approximately 10% TS and ground.

**Total solids and volatile solids determination.** TS and VS analyses were performed according to Standard Methods for the Examination of Water and Wastewater (2).
Table 7. Feed ration of cattle.

<table>
<thead>
<tr>
<th>Date of Ration Change</th>
<th>Physiological State of Cattle</th>
<th>Number of Cattle</th>
<th>Feed ration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>DPW&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>4/21/80</td>
<td>Milkers</td>
<td>131</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>140</td>
<td>20</td>
</tr>
<tr>
<td>6/2/80</td>
<td>Milkers</td>
<td>131</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>166</td>
<td>5</td>
</tr>
<tr>
<td>6/11/80</td>
<td>Milkers</td>
<td>130</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>68</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>6/24/80</td>
<td>Milkers</td>
<td>130</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>7/11/80</td>
<td>Dry</td>
<td>200</td>
<td>50</td>
</tr>
</tbody>
</table>

<sup>a</sup>Dihydrolyzed poultry waste.  
<sup>b</sup>Cottonseed hulls.  
<sup>c</sup>Hominy.  
<sup>d</sup>60% soybean, 20% corn pellets, 6% trace minerals, 5% CaCO<sub>3</sub>, 5% NaHCO<sub>3</sub>, 2% Vitaferm, 2% urea.  
<sup>e</sup>U.S.S. Standard blackstrap molasses.
Table 8. **Total solids and volatile solids concentration of manure.**

<table>
<thead>
<tr>
<th>Date of Collection</th>
<th>TS (% W/W)</th>
<th>VS (% W/W TS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/2/80</td>
<td>17.2 ± 0.2</td>
<td>81.0 ± 0.7</td>
</tr>
<tr>
<td>6/2/80</td>
<td>21.5 ± 0.5</td>
<td>78.8 ± 0.9</td>
</tr>
<tr>
<td>6/12/80</td>
<td>17.7 ± 0.2</td>
<td>79.0 ± 0.6</td>
</tr>
<tr>
<td>6/26/80</td>
<td>19.6 ± 1.6</td>
<td>71.6 ± 1.5</td>
</tr>
<tr>
<td>7/2/80</td>
<td>17.6 ± 0.2</td>
<td>76.9 ± 1.6</td>
</tr>
<tr>
<td>7/9/80</td>
<td>18.0 ± 0.8</td>
<td>74.7 ± 0.9</td>
</tr>
<tr>
<td>7/18/80</td>
<td>17.1 ± 0.6</td>
<td>67.5 ± 1.2</td>
</tr>
<tr>
<td>7/28/80</td>
<td>18.6 ± 0.7</td>
<td>72.7 ± 0.8</td>
</tr>
</tbody>
</table>
Total nitrogen determination. Total nitrogen analyses were performed according to Official Methods of Analysis of the Association of Official Analytical Chemists (4), Section 2.049. Results were expressed as % nitrogen (W/W).

Total phosphorous determination. Total phosphorous analyses were performed according to the Official Methods of Analysis of the Association of Official Analytical Chemists (4), Sections 2.019d - 2.025. Results were expressed as % (W/W) P₂O₅.

Total potassium determination. Total potassium analyses were performed according to Standard Methods for the Examination of Water and Wastewater (2). Concentrations were expressed in % (W/W) K₂O.

Ammonia analyses. Ammonia was analyzed with an Auto Analyzer and Technicon industrial method 18-69W with manifold #116-D001-01. This method was modified to include a dialyzer to remove particulate material from the manure since it interferes with the colorimetric analysis. In the modification employed, the sample is dialyzed prior to mixing with air and potassium sodium tartrate. The net effect of dialysis is to decrease the sensitivity by approximately 50%. Since ammonia concentrations in fresh manure and in digesters are higher than 75 mg/liter it was necessary to dilute the samples.

Analysis for methyl orange alkalinity. An Auto Analyzer using Technicon industrial method 23-69W and manifold #116-D015-01 was used to determine methyl orange alkalinity. The method was modified to include dialysis of the sample prior to its combination with the methyl orange reagent and air. The net effect of dialysis was to reduce the sensitivity by approximately 50%.
Sampling method for gaseous products. Gas volume was determined as previously described (41). One hundred ml serum bottles, which had been evacuated and flushed with carrier gas, were used for collection of samples for chromatographic analyses. Samples were taken through the rubber inlet hose with a double-tipped vacutainer needle (18-gauge).

Air drying analysis. Effluent samples (9 liters) were dried outdoors at ambient temperatures for 10 days in a wooden frame measuring 30 cm x 30 cm x 15 cm. The frame was placed in sandy soil so the top edge was even with the soil surface. The initial effluent depth was 10 cm.

Solids centrifugation analysis. Effluent samples (200 ml) were centrifuged in a Sorvall RC-5 refrigerated centrifuge at 19,000 x g for one hour at 4°C.

Volatile fatty acid sample preparation. Dairy cattle manure samples were centrifuged at 3,000 x g to remove solids. One ml of supernatant was diluted with 1 ml water in a glass-stoppered tube. Sodium chloride (0.8 g), 50% H₂SO₄ (0.4 ml), and chromatography grade ethyl ether (2.0 ml were added to each tube. The tubes were stoppered and mixed by inverting 20 times. The tubes were then centrifuged briefly to break the emulsion. The ether layer was recovered and placed in a clean tube containing MgSO₄ to remove water. This was allowed to stand for 10 min. before injecting a 5 ul samples into a gas-liquid chromatograph. Fatty acid concentration was determined by integration with a Spectra-Physics recording integrator (Model #SP4100). Four standards were prepared as described above containing formic, acetic, propionic, isobutyric, N-butyric, isovaleric, N-valeric, isocaproic and heptanoic acids at final concentrations of 0, 5, 10, and 20 meq/liter each.
**Volatile fatty acid analysis.** Chromatographic analysis of volatile fatty acids was determined on a Shimadzu gas-liquid chromatograph (Model GC7A) equipped with a dual flame ionization detector. Stainless steel columns, 1.83 m x 6.35 mm, containing 15% SP-2100/1% $\text{H}_3\text{PO}_4$ on 100/120 Chromosort W AW (Supelco, Inc.) were utilized to resolve the volatile fatty acid components of dairy cattle waste. Separation was achieved by the following temperature program: initial column temperature 135°C, 4 min. post injection time; temperature increased to 180°C at a rate of 16°C per min.; final temperature held for 8 min. Other instrument parameters and settings included the following: a nitrogen carrier gas at 60 cc/min.; injection temperature, 240°C; air pressure at 0.5 kg per cm$^2$; hydrogen pressure at 0.5 kg per cm$^2$; recorder chart speed 0.5 cm per min.

**Biogas analysis.** Chromatographic analysis of biogas for methane and carbon dioxide concentrations was determined on a Perkin-Elmer gas chromatograph (Model Sigma I) as previously described (41).
RESULTS

Effect of feed ration on biogas and methane production at a 6 day retention time. Biogas and methane production decreased within two to three days following addition of manure from cattle fed a different ration (Fig. 33). These determinations were made from the central digester at a 6 day retention time. Manure was not used for at least one day after collection to facilitate determination of total solids (TS) and volatile solids (VS). Methane and biogas production was highest on June 4, 1980, three weeks following the digester start up. Production was lowest on June 23, 1980, after the cattle feed ration was void of dihydrolyzed poultry waste (DPW) for eleven days. Methane and biogas production increased after June 23 until the feed ration was changed again on July 2, 1980. Methane and biogas production were reduced most when the concentration of CPW in the feed was decreased. Increasing the DPW concentration demonstrated a decreased amount of inhibition.

Effect of alkalinity and ammonia concentrations on biogas and methane production at a 6 day retention time. Alkalinity and ammonia concentrations were lowest when biogas and methane production were highest (Figs. 34, 35). The marked effect of the cattle feed ration changes is not evident. However, the highest ammonia and alkalinity concentrations of 79.8 mM and 6947 mg/liter occurred on June 25, 1980, the period in which DPW concentration was zero. The lowest ammonia concentration of 30.8 mM also occurred during the same period. The lowest
Fig. 33. The effect of dairy cattle feed ration changes on the production of biogas and methane during the anaerobic digestion of manure at a six day retention time. Symbols: (●) methane; (■) biogas; DPW – dihydrolyzed poultry waste.
Fig. 34. The effect of dairy cattle ration changes on ammonia concentrations during the anaerobic digestion of manure at a six day retention time. dpw = dihydrolyzed poultry waste.
Fig. 35. The effect of dairy cattle feed ration changes on methyl orange alkalinity concentrations during the anaerobic digestion of manure at a six day retention time. dpw = dihydrolyzed poultry waste.
alkalinity concentrations occurred when the DPW concentrations were the highest.

**Effect of feed ration on the volatile fatty acid concentrations during anaerobic digestion of manure at a 6 day retention time.** Volatile fatty acid (VFA) concentrations were highest when methane and biogas production were lowest (Table 9 and Fig. 33). Propionic acid concentrations were lowest when methane and biogas production were highest (Table 9 and Fig. 33). Acetate concentrations varied from this slightly, but the other VFAs followed the trend. The highest concentrations of all VFAs except acetic occurred on either 6/24/80 (0% DPW) or 6/25/80 (0% DPW). Acetate was highest on 6/7/80 (5% DPW). Biogas and methane production were at their highest levels from 6/3/80 to 6/9/80 (5% DPW) and at a low level on 6/23/80 (0% DPW).

**Fermentation in satellite digesters.** Fermentation products from the 10 satellite digesters were analyzed in the same manner as the central digester products. Data from July 13, 1980, and August 6, 1980, are in Tables 10, 11, and 12. Methane concentration and biogas production were higher in the satellites than in the central digester, while CO₂, ammonia, alkalinity concentrations, and volatile fatty acid concentrations were lower. Variation between the satellite digesters on any day was minimal.

**Solids recovery via centrifugation.** After centrifugation of the 6 day RT effluent at 19,000 x g for one hour, 69.77 ± 1.5% (W/W) was pelleted. Eight day RT effluent, which was treated in the same manner, was 79.0 ± 2.1% (W/W) pellet. Ten percent undigested manure (0 day) was 66.9 ± 1.1% (W/W) pellet. The centrifuge pellet was not firm and
Table 9. **Effect of feed ration on volatile fatty acid concentrations at a six day retention time.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Acetic</th>
<th>Propionic</th>
<th>Isobutyric</th>
<th>Butyric</th>
<th>Valeric</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/25/80</td>
<td>138.82 ± 0.29</td>
<td>35.39 ± 0.35</td>
<td>2.98 ± 0.04</td>
<td>10.29 ± 0.18</td>
<td>1.88 ± 1.12</td>
</tr>
<tr>
<td>5/27/80</td>
<td>161.49 ± 0.35</td>
<td>36.90 ± 0.43</td>
<td>3.06 ± 0.05</td>
<td>9.79 ± 0.13</td>
<td>1.87 ± 0.01</td>
</tr>
<tr>
<td>6/7/80</td>
<td>92.93 ± 3.36</td>
<td>29.47 ± 0.86</td>
<td>2.21 ± 0.07</td>
<td>6.04 ± 0.23</td>
<td>3.54 ± 2/75</td>
</tr>
<tr>
<td>6/12/80</td>
<td>134.93 ± 7.92</td>
<td>52.12 ± 6.67</td>
<td>4.80 ± 0.59</td>
<td>9.17 ± 1.05</td>
<td>2.40 ± 0.13</td>
</tr>
<tr>
<td>6/16/80</td>
<td>130.41 ± 4.73</td>
<td>27.98 ± 0.34</td>
<td>2.37 ± 0.01</td>
<td>7.44 ± 0.69</td>
<td>1.37 ± 0.01</td>
</tr>
<tr>
<td>6/24/80</td>
<td>132.85 ± 9.11</td>
<td>29.87 ± 0.71</td>
<td>2.91 ± 0.18</td>
<td>8.36 ± 0.23</td>
<td>3.56 ± 2.49</td>
</tr>
<tr>
<td>6/25/80</td>
<td>156.85 ± 6.40</td>
<td>43.16 ± 1.33</td>
<td>4.06 ± 0.17</td>
<td>12.52 ± 0.36</td>
<td>2.07 ± 0.13</td>
</tr>
<tr>
<td>6/26/80</td>
<td>105.59 ± 2.80</td>
<td>27.08 ± 0.94</td>
<td>2.51 ± 0.08</td>
<td>7.98 ± 0.25</td>
<td>1.63 ± 0.06</td>
</tr>
<tr>
<td>6/29/80</td>
<td>127.30 ± 2.04</td>
<td>35.10 ± 0.45</td>
<td>3.19 ± 0.05</td>
<td>10.25 ± 0.18</td>
<td>1.76 ± 0.20</td>
</tr>
<tr>
<td>7/1/80</td>
<td>120.13 ± 2.41</td>
<td>25.66 ± 0.29</td>
<td>2.46 ± 0.01</td>
<td>9.06 ± 0.12</td>
<td>1.36 ± 0.14</td>
</tr>
</tbody>
</table>

See Table 7 for description of feed ration on above dates.
<table>
<thead>
<tr>
<th>Digester name</th>
<th>CH₄ in gas phase (%)</th>
<th>Biogas production (L/L/day)</th>
<th>Methane production (L/L/day)</th>
<th>Ammonia (mM)</th>
<th>Alkalinity (mg CaCO₃/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>56.8 ± 0.2</td>
<td>1.81</td>
<td>1.03</td>
<td>28.0 ± 3.0</td>
<td>6227 ± 58</td>
</tr>
<tr>
<td>S2</td>
<td>55.3 ± 0.5</td>
<td>2.82</td>
<td>1.56</td>
<td>30.1 ± 1.0</td>
<td>6267 ± 247</td>
</tr>
<tr>
<td>S3</td>
<td>56.2 ± 0.1</td>
<td>2.58</td>
<td>1.45</td>
<td>27.2 ± 1.0</td>
<td>6255 ± 214</td>
</tr>
<tr>
<td>S4</td>
<td>53.2 ± 0.2</td>
<td>2.78</td>
<td>1.48</td>
<td>26.3 ± 0.3</td>
<td>5990 ± 77</td>
</tr>
<tr>
<td>S5</td>
<td>53.9 ± 0.3</td>
<td>2.77</td>
<td>1.49</td>
<td>29.4 ± 7.1</td>
<td>6153 ± 342</td>
</tr>
<tr>
<td>S6</td>
<td>55.0 ± 0.4</td>
<td>2.77</td>
<td>1.52</td>
<td>24.9 ± 2.3</td>
<td>5976 ± 197</td>
</tr>
<tr>
<td>S7</td>
<td>54.3 ± 0.3</td>
<td>2.87</td>
<td>1.56</td>
<td>24.9 ± 3.2</td>
<td>5932 ± 293</td>
</tr>
<tr>
<td>S8</td>
<td>55.5 ± 0.1</td>
<td>2.61</td>
<td>1.45</td>
<td>22.4 ± 4.2</td>
<td>6162 ± 200</td>
</tr>
<tr>
<td>S9</td>
<td>56.2 ± 0.1</td>
<td>2.47</td>
<td>1.39</td>
<td>26.4 ± 2.6</td>
<td>6080 ± 67</td>
</tr>
<tr>
<td>S10</td>
<td>58.2 ± 0.0</td>
<td>2.78</td>
<td>1.62</td>
<td>25.5 ± 0.4</td>
<td>5765 ± 378</td>
</tr>
<tr>
<td>Mean</td>
<td>55.5 ± 1.5</td>
<td>2.62 ± 0.31</td>
<td>1.46 ± 0.16</td>
<td>26.5 ± 2.3</td>
<td>6080 ± 173</td>
</tr>
<tr>
<td>Variance</td>
<td>1.95</td>
<td>0.088</td>
<td>0.024</td>
<td>4.71</td>
<td>23929.61</td>
</tr>
</tbody>
</table>
Table 11. Satellite digester fermentation products from 8/6/80.

<table>
<thead>
<tr>
<th>Digester name</th>
<th>CH₄ in gas phase (%)</th>
<th>Biogas production (L/L/day)</th>
<th>Methane production (L/L/day)</th>
<th>Ammonia mM</th>
<th>Alkalinity (mg CaCO₃/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>61.5 ± 0.2</td>
<td>1.40</td>
<td>0.86</td>
<td>36.1 ± 5.2</td>
<td>--^a</td>
</tr>
<tr>
<td>S2</td>
<td>61.7</td>
<td>1.29</td>
<td>0.80</td>
<td>76.7 ± 6.0</td>
<td>6436 ± 36</td>
</tr>
<tr>
<td>S3</td>
<td>64.8</td>
<td>1.19</td>
<td>0.77</td>
<td>33.4 ± 3.2</td>
<td>6434 ± 22</td>
</tr>
<tr>
<td>S4</td>
<td>61.6</td>
<td>1.46</td>
<td>0.90</td>
<td>31.6 ± 0.6</td>
<td>6310 ± 37</td>
</tr>
<tr>
<td>S5</td>
<td>64.2</td>
<td>1.58</td>
<td>1.01</td>
<td>31.9 ± 1.6</td>
<td>6189 ± 16</td>
</tr>
<tr>
<td>S6</td>
<td>64.2 ± 0.4</td>
<td>1.45</td>
<td>0.93</td>
<td>32.2 ± 3.2</td>
<td>5899 ± 486</td>
</tr>
<tr>
<td>S7</td>
<td>61.5 ± 0.1</td>
<td>1.28</td>
<td>0.79</td>
<td>29.4 ± 1.8</td>
<td>5130 ± 827</td>
</tr>
<tr>
<td>S8</td>
<td>65.0 ± 0.0</td>
<td>--^a</td>
<td>--^a</td>
<td>31.9 ± 1.1</td>
<td>6073 ± 299</td>
</tr>
<tr>
<td>S9</td>
<td>61.6 ± 0.2</td>
<td>1.30</td>
<td>0.80</td>
<td>35.0 ± 0.8</td>
<td>6198 ± 341</td>
</tr>
<tr>
<td>S10</td>
<td>64.2 ± 0.3</td>
<td>1.45</td>
<td>0.93</td>
<td>30.6 ± 0.5</td>
<td>6012 ± 310</td>
</tr>
</tbody>
</table>

Mean 63.0 ± 1.6  1.38 ± 0.12  0.87 ± 0.08  32.8 ± 3.2  6142 ± 354

Variance 2.17  0.013  0.006  5.11  141169.11

^a Sample destroyed
Table 12. Satellite digester volatile fatty acid concentrations from 7/13/80 and 8/6/80.

<table>
<thead>
<tr>
<th>Di­ges­ter Name</th>
<th>Acetic</th>
<th>Propionic</th>
<th>Isobutyric</th>
<th>Butyric</th>
<th>Valeric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7/13 8/6</td>
<td>7/13 8/6</td>
<td>7/13 8/6</td>
<td>7/13 8/6</td>
<td>7/13 8/6</td>
</tr>
<tr>
<td>S1</td>
<td>12.84 ± 0.09 8.25 ± 0.02</td>
<td>17.66 ± 0.06 19.53 ± 0.49</td>
<td>1.04 ± 0.01 0.81 ± 0.01</td>
<td>0.66 ± 0.06 0.61 ± 0.30</td>
<td>1.18 ± 0.47 0.66 ± 0.33</td>
</tr>
<tr>
<td>S2</td>
<td>14.66 ± 0.15 16.81 ± 0.27</td>
<td>18.22 ± 0.10 19.40 ± 0.20</td>
<td>1.06 ± 0.04 0.96 ± 0.02</td>
<td>0.56 ± 0.09 2.41 ± 0.63</td>
<td>0.33 ± 0.25 0.72 ± 0.38</td>
</tr>
<tr>
<td>S3</td>
<td>NDa 14.47 ± 0.40</td>
<td>ND 20.62 ± 0.76</td>
<td>ND 0.65 ± 0.02</td>
<td>ND 1.92 ± 0.08</td>
<td>ND 0.99 ± 0.27</td>
</tr>
<tr>
<td>S4</td>
<td>19.44 ± 0.33 15.77 ± 0.47</td>
<td>24.01 ± 0.40 19.20 ± 0.44</td>
<td>1.50 ± 0.05 0.66 ± 0.00</td>
<td>2.76 ± 0.21 1.26 ± 0.01</td>
<td>0.32 ± 0.03 0.41 ± 0.01</td>
</tr>
<tr>
<td>S5</td>
<td>15.26 ± 0.05 15.26 ± 0.14</td>
<td>21.81 ± 0.39 23.03 ± 0.16</td>
<td>1.23 ± 0.03 0.73 ± 0.01</td>
<td>0.75 ± 0.44 1.85 ± 0.00</td>
<td>0.27 ± 0.00 1.13 ± 0.02</td>
</tr>
<tr>
<td>S6</td>
<td>14.65 ± 0.20 8.84 ± 0.11</td>
<td>22.73 ± 0.12 23.47 ± 0.17</td>
<td>1.33 ± 0.00 0.47 ± 0.01</td>
<td>1.05 ± 0.06 0.85 ± 0.02</td>
<td>3.63 ± 0.39 1.25 ± 0.50</td>
</tr>
<tr>
<td>S7</td>
<td>15.37 ± 0.18 14.26 ± 0.30</td>
<td>21.28 ± 0.04 23.04 ± 0.52</td>
<td>1.26 ± 0.01 0.98 ± 0.02</td>
<td>1.15 ± 0.44 1.09 ± 0.02</td>
<td>0.15 ± 0.09 0.54 ± 0.01</td>
</tr>
<tr>
<td>S8</td>
<td>10.10 ± 11.99 ± 0.00</td>
<td>15.47 ± 22.39 ± 0.02</td>
<td>0.82 ± 2.16 ± 0.02</td>
<td>0.41 ± 2.54 ± 0.01</td>
<td>2.14 ± 2.30 ± 0.11</td>
</tr>
<tr>
<td>S9</td>
<td>17.21 ± 0.60 12.27 ± 0.13</td>
<td>23.04 ± 0.23 14.84 ± 0.18</td>
<td>1.91 ± 0.01 0.85 ± 0.01</td>
<td>1.96 ± 0.01 1.08 ± 0.01</td>
<td>0.69 ± 0.01 0.22 ± 0.01</td>
</tr>
<tr>
<td>S10</td>
<td>9.83 ± 0.05 12.07 ± 0.09</td>
<td>16.96 ± 0.01 13.79 ± 0.15</td>
<td>0.96 ± 0.01 0.69 ± 0.01</td>
<td>1.11 ± 0.20 1.42 ± 0.40</td>
<td>1.48 ± 0.59 0.16 ± 0.00</td>
</tr>
<tr>
<td>Mean</td>
<td>14.37 ± 3.10 13.00 ± 2.78</td>
<td>20.13 ± 3.08 19.93 ± 3.31</td>
<td>1.23 ± 0.32 0.89 ± 0.46</td>
<td>1.15 ± 0.75 1.50 ± 0.66</td>
<td>1.13 ± 1.15 0.84 ± 0.63</td>
</tr>
<tr>
<td>Variance</td>
<td>8.55 7.33</td>
<td>8.44 10.39</td>
<td>0.09 0.20</td>
<td>0.51 0.42</td>
<td>1.17 0.39</td>
</tr>
</tbody>
</table>

aN: Sample destroyed
the solids readily resuspended. Separatory aids were not utilized.

**Solids recovery via air drying.** Air drying on a sand bed for 10 days removed 94.5% (W/W) of the water from 6 day RT effluent. Air drying removed 88.6% (W/W) and 82.4% (W/W) of the water from 0 day RT and 8 day RT effluent respectively. The lower amount of water removal in the 0 and 8 day RT effluent can be attributed to a greater incidence of rain during the 10 day drying period. The dried material was 43.2%, 63.3%, and 40.7% (W/W) TS for retention times of 0, 6, and 8 days.

**Fertilizer value of digester effluent and components.** The N-P-K values for 0, 6 and 8 day RT effluents and their components are in Table 13. The effluents contained high levels of K₂O which was evenly distributed between solids and supernate. Nitrogen and P₂O₅ concentrations were highest in the digester solids. Nutrient loss was determined by calculation using the N-P-K values of uncentrifuged effluent as the reference.
Table 13. Fertilizer value of digester effluents and components.

<table>
<thead>
<tr>
<th></th>
<th>%N</th>
<th>%P₀₂</th>
<th>%K₀₂</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0 day RT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>effluent</td>
<td>0.27 ± 0.03</td>
<td>0.32 ± 0.00</td>
<td>4.55 ± 0.27</td>
</tr>
<tr>
<td>air dried</td>
<td>0.91 ± 0.19</td>
<td>1.12 ± 0.06</td>
<td>7.22 ± 0.54</td>
</tr>
<tr>
<td>cent. solids</td>
<td>0.62 ± 0.01</td>
<td>0.64 ± 0.00</td>
<td>4.40 ± 0.27</td>
</tr>
<tr>
<td>cent. supernate</td>
<td>0.15 ± 0.05</td>
<td>0.12 ± 0.00</td>
<td>3.76 ± 0.00</td>
</tr>
<tr>
<td><strong>6 day RT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>effluent</td>
<td>1.29 ± 0.03</td>
<td>0.26 ± 0.07</td>
<td>6.33 ± 0.24</td>
</tr>
<tr>
<td>air dried</td>
<td>4.53 ± 0.47</td>
<td>2.33 ± 0.11</td>
<td>9.11 ± 0.54</td>
</tr>
<tr>
<td>cent. solids</td>
<td>2.79 ± 0.38</td>
<td>0.78 ± 0.03</td>
<td>4.40 ± 0.54</td>
</tr>
<tr>
<td>cent. supernate</td>
<td>0.64 ± 0.05</td>
<td>0.12 ± 0.00</td>
<td>4.94 ± 0.39</td>
</tr>
<tr>
<td><strong>8 day RT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>effluent</td>
<td>0.33 ± 0.06</td>
<td>0.38 ± 0.03</td>
<td>4.71 ± 0.94</td>
</tr>
<tr>
<td>air dried</td>
<td>0.97 ± 0.02</td>
<td>1.09 ± 0.06</td>
<td>7.54 ± 0.00</td>
</tr>
<tr>
<td>cent. solids</td>
<td>0.66 ± 0.13</td>
<td>0.74 ± 0.00</td>
<td>5.02 ± 0.54</td>
</tr>
<tr>
<td>cent. supernate</td>
<td>0.00 ± 0.00</td>
<td>0.12 ± 0.00</td>
<td>4.71 ± 0.00</td>
</tr>
</tbody>
</table>
Table 14. Loss of nutrients during ten day air drying.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</th>
<th>K&lt;sub&gt;2&lt;/sub&gt;O</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 day RT</td>
<td>37.7%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>35.3%</td>
<td>70.6%</td>
</tr>
<tr>
<td>6 day RT</td>
<td>51.8%</td>
<td>-23.2%&lt;sup&gt;b&lt;/sup&gt;</td>
<td>80.2%</td>
</tr>
<tr>
<td>8 day RT</td>
<td>20.5%</td>
<td>22.7%</td>
<td>56.7%</td>
</tr>
</tbody>
</table>

<sup>a</sup> Loss was calculated from N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O concentrations before and after drying. TS concentrations were 8.0, 8.7, 10.8% (W/W) before drying and 43.2, 63.3, and 40.7% (W/W) after drying.

<sup>b</sup> Indicates increase.
DISCUSSION

This study investigated three areas: the feasibility of using a multistream, multistage digestion system for dairy cattle waste; the effect of cattle feed variation on methane production; and fertilizer value of the digester effluent.

A multistream, multistage design was investigated for two reasons: first, to determine the feasibility of utilizing plastic bag type digesters for small anaerobic digestion installations; and second, to facilitate approaching continuous fermentation. Generally, research on methane production has been done in 3 - 10 liter vessels, in which substrate addition occurred once or twice per day (29, 41). The digester design utilized in this study approached continuous fermentation. Substrate was added to the central and satellite digesters 24 and 72 times per day respectively. The central digester was operated at a 6 day RT while the satellites were operated at a 2 day RT. Substrate for the satellite digesters was the central digester effluent. The digester system functioned well after three preliminary runs. These preliminary runs were necessary to identify and correct any design and construction flaws. One area that was corrected was the positioning of the satellite digester feed valves. Initially, they were placed in a downward position from the central digester recirculatory pipe. Solids flowing through the pipe would collect at the top of the valve and plug it. This problem was solved by placing the valves in an up-
wards position which stopped the solids from settling. Another problem that was encountered was the central digester construction material. Initially, clear polyvinylchloride waterbed material was used. After a period of time, the bag split. It was replaced with PVC which had a nylon weave for additional strength. This material also split after a relatively short time. It appears that conventional materials should be used in the digester design.

The digester design also facilitates using a three-factorial experimental design. Studies on the effect of various parameters can be performed in nine of the satellites with the tenth being used as a control. If the experimentation results in the complete inhibition of methane production, the digester can be emptied and refilled immediately. This results in little "down time". Preliminary results of three-factorial experimentation indicate that the system can be used efficiently and the satellite digesters stabilize within three to four days after refilling. Results presented in this study show that variability between the satellite digesters on any given day is small.

The effect of the dairy cattle feed ration on methane production was pronounced. At a 6 day RT methane production decreased from 1.26 liters CH₄/liter of reactor/day to 0.3 liters/day. The concentration of poultry waste in the ration decreased from 20% to 0%. Methane production decreased again when the concentration of poultry waste was changed from 0% to 20%, but the decrease was not as great. The results cannot be attributed directly to the presence or absence of poultry waste in the feed. The results can, however, be correlated to a change in the concentrations of the components in the feed ration. The data
indicate that the population of bacteria present in the digester, when the feed ration contained 20% poultry waste, was unable to produce methane as efficiently at lower poultry waste concentrations. After a new population was established at the lower concentrations, methane production increased. This eliminates the possibility that the higher methane production rates could be attributed to a growth factor being present in the poultry waste. If the increased production was due to a growth factor, methane production would have remained low for the entire period in which the feed ration was void of poultry waste. The results also indicated that methane production was not decreased as much by addition of manure from cattle fed a ration containing higher concentrations of poultry waste. However, the methane production was decreased.

Ammonia concentrations were inversely proportional to methane and biogas production. The marked effect of feed ration changes was not evident, however. Alkalinity concentrations were high (less than 6000 mg/liter, but were within levels reported by other investigators (41). A direct relationship between alkalinity concentrations and methane production or feed ration changes was not evident.

Volatile fatty acid concentrations were inversely proportional to biogas and methane production. A relationship between VFA concentration and feed ration changes cannot be made due to the limited number of samples analysed. A correlation would be expected, however, based upon the effect of ration changes on biogas production and the relationship between VFA concentration and biogas production.

The changes in rate of methane production are important from a
commercial standpoint. The anaerobic digestion of dairy cattle waste for pollution abatement and energy production is now being investigated extensively. Investigators reporting high yields of methane generally utilize manure from cattle fed a consistent diet (29, 41). Variations in cattle feed rations will increase as the costs of the ration components fluctuate. These variations could have a marked effect on a commercial digester operation. Further study is needed to determine the factors which effect methane production when the cattle feed ration varies. The marked effect might be overcome by making gradual changes in the cattle feed ration.

The recovery of digester solids on a commercial basis generally utilizes centrifugation and vacuum filtration. The costs associated with these methods are high (44). Effluent was centrifuged, separated, and nitrogen, $P_2O_5$ and $K_2O$ concentrations determined for 0, 6 and 8 day RT. The results indicate that the majority of the nitrogen and $P_2O_5$ is in the centrifuge solids. Potassium concentrations were evenly distributed between supernate and pellet.

Air drying on a sand bed was studied as an alternative to centrifugation. Air drying for 10 days removed 88.6, 94.5, and 82.4% of the total water present in 0, 6 and 8 day RT effluent. The higher water removal from 6 day RT effluent can be attributed to a lower incidence of rain during the drying period. Nitrogen, $P_2O_5$ and $K_2O$ concentrations were highest in the dried 6 day RT effluent. These higher levels can be attributed to an increased concentration of solute due to more efficient water removal. Nutrient loss during drying was from 56.7 to 80.6% for $K_2O$ and 20.5 to 51.8% for nitrogen. Phosphorous loss was
35.3 and 22.7% for 0 and 8 day RT effluent. The increase of phosphorous in 6 day RT effluent is unexplained. Air drying beds on a commercial scale would have drainage pipes under them. This would increase water removal and facilitate recovery of a portion of the nutrients lost through percolation.

The results from this study indicate the following: first, the multistage, multistream laboratory digester can be used for the study of methane production from dairy cattle waste; second, variation in cattle feed ration has a marked effect on methane production; third, air drying can efficiently be used for solids concentration and recovery.
GENERAL DISCUSSION

The economic and technical feasibility of digesting dairy cattle waste to methane and other vendable products was analysed.

The effect of refractory volatile solids concentration and reaction rate constant on the economics of bioconversion of dairy waste were studied using a computer model. The refractory volatile solids concentrations were varied between 28% and 52%. Retention time was varied between 1 and 10 days at a temperature of 55°C. The reaction rate constant was varied between $5.92 \times 10^9$ and $1.24 \times 10^{11}$. The value of $5.92 \times 10^9$ was determined by Ashare et al. (3) through a least squares fit of experimental data obtained by several investigators. This was the minimum attainable rate. The higher values used were estimates of potential increases in rate that might be obtained if the fermentation was optimized by strain selection, physical and chemical parameters, and nutritional techniques. Aerobic fermentations have been optimized by a combination of these techniques. Rates of fermentation and increases in total yields of desired products are commonplace. The values used were 1.5, 2.0, 2.5, 3.0, 6.0, 11.0, and 20.9 times the rate calculated by Ashare.

The technical analysis of the digestion process investigated three areas: the feasibility of using a multistream, multistage digestion system for dairy cattle waste; the effect of cattle feed variation on methane production; and fertilizer value of the digester effluent. A
multistream, multistage design was investigated for two reasons: first, to determine the feasibility of utilizing plastic bag type digesters for small anaerobic digestion installations; and second, to facilitate approaching continuous fermentation. Generally, research on methane production has been done in 3 - 10 liter vessels in which substrate addition occurred once or twice per day (29, 41). The digester design utilized in this study approached continuous fermentation. Substrate was added to the central and satellite digesters 24 and 72 times per day respectively. The central digester was operated at a 6 day RT, while the satellites were operated at a 2 day RT. Substrate for the satellite digesters was the central digester effluent. The digester system functioned well after three preliminary runs. The preliminary runs were necessary to identify and correct design and construction flaws which included the central digester material and the position of the satellite digester feed valves.

The digester design also facilitates using a three factorial experimental design. Studies on the effect of various parameters can be performed in nine of the satellites with the tenth being used for a control. If the experimentation results in the complete inhibition of methane production, the digester can be emptied and refilled immediately. This results in little "down time". Results presented in this study show that variability between the satellite digesters on any given day was small.

The effect of the ingredients used in the dairy cattle feed ration on methane production was pronounced. When the concentration of dihydrolyzed poultry waste in the ration was decreased from 20% to 0%,
methane production decreased from 1.26 liters CH\(_4\) per liter of reactor per day to 0.3 liter per liter/day. Methane production decreased again when the concentration of poultry waste was changed from 0% to 20%, but this decrease was not as great. The results cannot be attributed directly to the presence of poultry waste in the feed. The results can, however, be correlated to a change in the concentrations of the components in the feed ration. The data indicate that the population of bacteria present in the digester, when the feed ration contained 20% poultry waste, was unable to produce methane as efficiently at lower poultry waste concentrations. After a new population was established at the lower concentrations, methane production increased. This eliminates the possibility that the higher methane production rates could be attributed to a growth factor being present in poultry waste. If the increased production was due to a growth factor, methane production would have remained low for the entire period in which the feed ration was void of poultry waste. The results also indicated that methane production was not decreased as much by addition of manure from cattle fed a ration containing higher concentrations of poultry waste. However, the methane production was decreased.

Ammonia concentrations were inversely proportional to methane and biogas production. The marked effect of feed ration changes was not evident, however. Alkalinity concentrations were high (6000 mg/liter), but were within levels reported by other investigators. A direct relationship between alkalinity concentrations and methane production or feed ration changes was not evident.

The anaerobic digestion of dairy cattle waste to methane and other
vendable products must be economical if it is to be a viable option for pollution abatement. The fluctuations in methane production due to cattle feed ration change could have a significant impact on the production cost. Computerized modeling of the digestion process economics by Wodzinski et al. (43, 44) have determined that this process is economical if the solids are recovered from the digester effluent and upgraded to a 6-6-6 fertilizer before sale. Without this type of solids recovery, the process is uneconomical at any of the reaction rate constants and refractory volatile solids concentrations studied in Section I. The lowest unit gas cost without a fertilizer plant reported in this study was more than $8.00 per M. cu. ft. methane. The present price of methane in Florida is less than one-third of this production cost. However, incorporation of a fertilizer plant into the calculation resulted in unit gas costs lower than the market price.

Studies conducted in Section II investigated the fertilizer characteristics of the digester effluent. The recovery of digester solids on a commercial basis generally utilizes centrifugation and vacuum filtration. The costs associated with these methods are high. Effluent was centrifuged, separated, and nitrogen, $P_2O_5$, and $K_2O$ conc. determined for 0, 6, and 8 day RT. The results indicate that the majority of the nitrogen and $P_2O_5$ is in the centrifuge solids. Potassium concentrations were evenly distributed between supernatant and pellet.

Air drying on a sand bed was studied as an alternative to centrifugation. Air drying for 10 days removed 88.6, 94.5, and 82.4% of the total water present in 0, 6, and 8 day RT effluent. The higher water
removal from 6 day RT effluent can be attributed to a lower incidence of rain during the drying period. Nitrogen, P$_2$O$_5$, and K$_2$O concentrations were highest in the dried 6-day RT effluent. These higher levels can be attributed to an increased concentration of solute due to more efficient water removal. Nutrient loss during drying was from 56.7 to 80.6% for K$_2$O and 20.5 to 51.8% for nitrogen. Phosphorous loss was 35.3 and 22.7% for 0 and 8 day RT effluent. The increase of phosphorous in 6 day RT effluent is unexplained. Air drying beds on a commercial scale would have drainage pipes incorporated into their design. This would increase water removal and facilitate recovery of the soluble portion of the nutrients lost through percolation.

The economic analysis presented indicates that the digestion process can be economical if methane and other vendable products are recovered from the system. It also suggests that the process should be optimized for maximum methane production and minimum solids degradation at the shortest possible retention time necessary for solids stabilization. This would result in a higher profit-to-cost ratio and increase the feasibility of utilizing the process for pollution abatement.

The results of the technical study support the conclusion that the multistage, multistream laboratory digester can be used to study the production of methane from dairy cattle waste. The results indicate that methane production is adversely affected by drastic changes in the cattle feed ration and also indicate solids concentration and recovery can be efficiently facilitated with air drying.
GENERAL SUMMARY

The production of methane and other vendable products from dairy cattle waste has been proposed as a method for pollution abatement. The results presented in this study identify some of the factors that influence the technical and economic parameters that must be used to successfully abate pollution in Okeechobee County.

An economic investigation of the digestion process conducted with a computerized cost model identified the following:

Volatile solids conversion and annual methane production were lowest (16.7%, 9.4 x 10^4 M. cu. ft.) at a high refractory volatile solids concentration (52%) and a short retention time (1 day).

Volatile solids conversion and annual methane production were highest (60.6%, 3.4 x 10^5 M. cu. ft.) at a low refractory volatile solids concentration (28%) and a long retention time (10 days).

The reaction rate constant used in the calculation listed above was 5.92 x 10^9.

When the reaction rate constant is varied, the values calculated above were directly proportional to the reaction rate constant.

The unit gas cost, when calculated without incorporation of a fertilizer plant, was lowest ($9.74 per M. cu. ft.) at a low refractory volatile solids concentration (28%), long retention time (10 days) and high total solids concentration (14%). The highest unit gas cost without a fertilizer plant ($32.75) occurred at a high refractory volatile
solids concentration (52%), short retention time (1 day) and low total solids concentration (8%). The reaction rate constant used was $5.92 \times 10^9$ and the unit gas cost was inversely related to the reaction rate constant when calculated without the fertilizer plant.

The unit gas cost did not approach the present market price at the largest reaction rate studied.

The unit gas cost, when calculated with the incorporation of a fertilizer plant was lowest ($0.90) at a high refractory volatile solids concentration (52%), short retention time (1 day), high total solids concentration (14%) and large reaction rate constant ($1.24 \times 10^{11}$).

The highest unit gas cost with a fertilizer plant ($9.23) occurred at a low refractory volatile solids concentration (28%), short retention time (1 day), low total solids concentration (8%) and a large reaction rate constant ($1.24 \times 10^{11}$).

The unit gas cost at 10% total solids, 52% refractory volatile solids and a reaction rate of $5.92 \times 10^9$ did not fluctuate widely at 3 ($1.97$ per M. cu. ft.), 4 ($1.58$ per M. cu. ft.), and 5 ($1.98$ per M. cu. ft.) day retention times. These are the conditions that are indicated to be the most stable from an economical and technological attitude.

Experimental results were obtained utilizing a multistream, multiflow digester design that approached continuous feed conditions. Process conditions included a temperature of $55^\circ$C, 10% total solids, and retention times of 2 and 6 days in the satellite and central digesters. The central digester effluent served as influent for the satellite digesters resulting in a total retention time of 8 days. The sub-
strate used in the central digester was collected from a commercial dairy near Orlando, Florida, and included feces and urine. The total solids concentrations ranged between 17.2 and 21.5% (W/W), while volatile solids concentrations varied between 67.5 and 81.0%. The ration fed to the cattle changed 5 times during the course of the study.

The following experimental parameters were identified in the multi-stage, multistream apparatus:

Feed ration changes produced a significant effect on total gas and methane production. Methane production decreased from 1.3 to less than 0.3 liters per liter reactor fluid per day due to a change in the cattle feed ration. These changes could not be attributed to either a growth enhancing or inhibiting compound present in the various rations, but are probably the result of the selection for different microbial populations.

Alkalinity and ammonia concentrations were lowest when biogas and methane production was highest. Ammonia concentrations ranged from 30.8 mM to 79.8 mM. Alkalinity concentrations ranged between 6150 mg per liter and 6947 mg per liter.

Variability between the ten satellite digesters was minimal on any given day, but all fluctuated with time.

Analysis of the digester effluent indicated that nitrogen and phosphate concentrations were highest in the solids while the potassium concentrations were evenly distributed.

Air drying of the digester effluent removed 82.4 to 94.5% of the water in 10 days. This resulted in N, P, and K concentrations of 4.5%,
2.3%, and 9.1% in the driest sample.

The results of this study indicate that the anaerobic digestion of dairy cattle waste to methane and other vendable products is both technically and economically a viable option for pollution abatement. However, further research is needed to optimize the process for maximum methane production with minimal solids degradation at the shortest retention times necessary to stabilize the effluent solids. Further investigation is needed to determine if the process can be favorably influenced by the addition of various chemicals such as cobalt. The upgrading and use of the digester solids as fertilizer should be studied to determine its characteristics as fertilizer and as a possible soil conditioner. Studies are also required to determine the heavy metal concentrations present in the effluent.
Appendix I. Computer model output listing a complete economic analysis without brute force iteration.

### OPTIMUM DESIGN FOR
### A PLUG FLOW DIGESTER

#### IMPLEMENTING PLASTIC BAG WITH A CENTRIFUGE
#### WITHOUT A HEAT EXCHANGER
#### GAS TO INTERSTATE PIPELINE

### FEED MAKEUP

<table>
<thead>
<tr>
<th>Number of Animals</th>
<th>Rate of Manure Production</th>
<th>Moisture Content of Manure</th>
<th>Volatile Solids</th>
<th>Refractory Volatile Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>26600</td>
<td>9.49 lbs/animal/day</td>
<td>89.5%</td>
<td>85.0%</td>
<td>52.0%</td>
</tr>
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</table>

### PROCESS CONDITIONS AT MINIMUM UNIT GAS COST

#### Flow Streams

| Stream                  | Flow Rate | Temp | Vol.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bleed Stream</td>
<td>0.1420E+04</td>
<td>20</td>
<td>89.5</td>
</tr>
<tr>
<td>Recycle Stream</td>
<td>0.0020E+00</td>
<td>20</td>
<td>89.5</td>
</tr>
<tr>
<td>Water Make-up</td>
<td>0.0020E+00</td>
<td>20</td>
<td>89.5</td>
</tr>
<tr>
<td>Temperature of Make-up Water</td>
<td>0.2657E+03</td>
<td>20</td>
<td>89.5</td>
</tr>
<tr>
<td>Solids in Centrifuge Pellet</td>
<td>25.0</td>
<td>20</td>
<td>89.5</td>
</tr>
</tbody>
</table>

#### Heat Balance

| Source                  | Flow Rate | Temp | Vol.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat loss from digesters</td>
<td>0.1458E+08</td>
<td>20</td>
<td>89.5</td>
</tr>
<tr>
<td>Evaporative cooling</td>
<td>0.9439E+07</td>
<td>20</td>
<td>89.5</td>
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<tr>
<td>Heat loss with bleed</td>
<td>0.2657E+08</td>
<td>20</td>
<td>89.5</td>
</tr>
<tr>
<td>Heat loss with gas</td>
<td>0.1737E+07</td>
<td>20</td>
<td>89.5</td>
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<tr>
<td>Heat loss with cent. sols</td>
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<td>20</td>
<td>89.5</td>
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<tr>
<td>Heat in recycle water</td>
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<td>89.5</td>
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<td>Heat of reaction</td>
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<td>89.5</td>
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<td>Heat loss with L.H.R.</td>
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<td>89.5</td>
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<tr>
<td>Waste heat from plant gen</td>
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<tr>
<td>Heat to dry fertilizer</td>
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<td>89.5</td>
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<tr>
<td>Total heat requirements</td>
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<td>89.5</td>
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</table>

#### Power Requirements

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Power Rate</th>
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<tbody>
<tr>
<td>Predigester mixing</td>
<td>0.1104E+02</td>
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<tr>
<td>Digestor, mixing</td>
<td>0.4457E+00</td>
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<tr>
<td>Fluid pumping</td>
<td>0.1733E+03</td>
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<tr>
<td>Dehydrator</td>
<td>0.6258E+01</td>
</tr>
<tr>
<td>Gas Compressor</td>
<td>0.4457E+00</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>Recycle pump</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>Total Power Requirements</td>
<td>0.3937E+03</td>
</tr>
</tbody>
</table>

#### Economic Analysis of the Digester System

### Capital Investment (in Dollars)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premix Unit</td>
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</tr>
<tr>
<td>Pumps</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Dehydrator (if needed)</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Gas Compressor</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Sludge Drying Bed</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Piping</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Instrumentation and Controls</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Recirculation Pump</td>
<td>0.1717E+00</td>
</tr>
<tr>
<td>Fertilized Plant</td>
<td>0.1717E+00</td>
</tr>
</tbody>
</table>
TOTAL CAPITAL INVESTMENT

CONTRACTS FEE (0.1% TOT. CAP. INV.)
ENGINEERING (0.05% TOT. CAP. INV.)
GAS COMPRESSION PIPING
SCHER FOR MANURE TRANSPORT
CAPITAL TO CONFINE CATTLE

PROJECT CONTINGENCY (0.15% SUB. PL. INV.)
TOTAL PLANT INVESTMENT

MANUFACTURING COST (IN DOLLARS/YEAR)
RAW MATERIAL
COST TO SUPPLEMENT SOLIDS w/NPK
WATER MAKEUP (10,400GILL./M GAL)
STEAM (4,900GILL./MH BTU)

OPERATING LABOR 4 MEN AT 0.00DOL./HH
MAINTENANCE LABOR (0.015% TOT. PL. INV.)
ADJN. OVERHEAD (0.02% TOT. MAINT. LABOR)
OPERATING SUPPLIES (0.015% TOT. PL. INV.)
LOCAL TAXES/INSURANCE (0.012% TOT. PL. INV.)
TOTAL FERTILIZER PLANT LABOR

FERTILIZER PLANT INSURANCE
TOTAL GRASS OPERATING COST
CREDIT FOR FERTILIZER
CREDIT FOR CO2
CREDIT FOR FARM ELECTRICITY
TOTAL NET OPERATING COST

WHEN TOTAL NET OPERATING COST IS NEGATIVE, THE CREDITS FOR CO2 AND FERTILIZER EXCEED THE TOTAL NET OPERATING COST CALCULATION OF TOTAL CAPITAL REQUIREMENT

TOTAL PLANT INVESTMENT
INTEREST DURING CONSTRUCTION (9.0 PERCENT*101 TOT. PL. INV.*1.8775)
START-UP (0.1% TOT. GR. SUPER. COST)
WORKING CAPITAL (0.02% TOT. PL. INV.)

UNIT GAS COST CALCULATION

INTEREST ON DEBT 9.00 PERCENT
RETURN ON EQUITY 15.00 PERCENT
RETURN ON RENT BASE 15.50 PERCENT
FEDERAL TAX RENT 48.00 PERCENT

TOTAL NET OPERATING COST
DEPRECIATION 0.16403E 07 DOLLARS
RETURN ON RENT BASE 0.19949E 06
FEDERAL INCOME TAX 0.29421E 07 DOLLARS

TOTAL GAS REVENUE REQUIREMENT PER YEAR
ANNUAL GAS PRODUCTION
NET ANNUAL GAS PRODUCTION

UNIT GAS COST
NET ANNUAL CH4 PRODUCTION (0$1,96 M CU FT)

DIGESTER OPERATING CONDITIONS

TEMPERATURE 50.0 DEG. C
RETENTION TIME 10.0 DAYS
VOLATILE SOLIDS IN DIGESTER 15.0 LBS/CU FT.
PERCENT SOLIDS IN DIGESTER 11.0
NUMBER OF DIGESTERS 279.

TOTAL DIGESTER VOLUME 0.26312E 06 M CU FT.
GAS PRODUCTION 0.26312E 06 M CU FT./YEAR
UNIT GAS COST 0.41535E 01 DOLL./M CU FT.

NET ANNUAL PROFIT 0.18039E 07 DOLLARS/YEAR

IMPACT ON RELEASING POLLUTION INTO LAKE DIELCHENOE EXCLUDING THE W. ANP P. REMOVED BY LAGUONS

NITROGEN REMOVED 0.23036E 03 TUNS/YEAR
PHOSPHORUS REMOVED 0.78470E 02 TUNS/YEAR
Appendix II. Computer model output listing unit gas cost under different process conditions (temperature, retention time and digester influent solids using a brute force iteration.

**DESIGN OF A PLUG FLOW DIGESTER IMPLEMENTING PLASTIC BAG WITH CENTRIFUGE WITHOUT HEAT EXCHANGER GAS TO INTERSTATE PIPELINE**

**FEED MAKEUP:**
- **NUMBER OF ANIMALS = 26600.0**
- **RATE OF MANURE PRODUCTION = 8.49 LBS OF SOLIDS/DAY/ANIMAL**
- **MOISTURE CONTENT OF MANURE = 87.5 PERCENT**
- **VOLATILE SOLIDS = 82.0 PERCENT OF TOTAL SOLIDS**
- **REFRACTORY VOLATILE SOLIDS = 52.4 PERCENT OF VOLATILE SOLIDS**

**PATTERN MOVES IN ITERATION ROUTINE**

<table>
<thead>
<tr>
<th>Unit cost</th>
<th>T</th>
<th>HRT Days</th>
<th>SO Gm/L</th>
<th>Percent Solids</th>
<th>Gas prod. M cu. ft. per year</th>
<th>Heat req. MM BTU per day</th>
<th>Water Makeup M GPD</th>
<th>Power Req. HP</th>
<th>Water Recycle M GPD</th>
<th>Digester Volume M cu. ft.</th>
<th>Number of digesters</th>
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</thead>
<tbody>
<tr>
<td>-13.43</td>
<td>50.0</td>
<td>1.0</td>
<td>65.6</td>
<td>8.0</td>
<td>0.8366E 05</td>
<td>242.6</td>
<td>0.0</td>
<td>151.5</td>
<td>122.0</td>
<td>45.0</td>
<td>2.0</td>
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<td>1.0</td>
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The investigator selects the lowest unit gas cost consistent with the known activities of methanogenic microorganisms and utilizes these process conditions for further economic analyses of the system.
Appendix III. Computer program used for the economic analysis of the biocconversion of dairy manure to methane, fertilizer, and carbon dioxide. The program has capital cost factors for a 25 ton/day fertilizer plant. The digester and centrifuge cost factors were provided by Hamilton Standard.
COmpute Minimum Gas Cost For Each Value of Temp, Time, Solids

Determine Number of Steps in Range of Variable

BRUTE FORCE ITERATION ROUTINE

C******

continue

DO 2 1=1,7

1 iCPI=ICPI+1

iCTP=ICTP(4)

C Compute Minimum Gas Cost For Each Value of Temp, Time, Solids

DO 2 2=1,ICTP

2 CALL MUSE(1,OLD,TOTAL(1))

C ********************* DIGESTER

C**************
SUBROUTINE MODEL(J,BUILD,UGC,JB,NUM)

DIMENSION CONM(J),HERON,SH,VFS,DZ2E,RK2U,H,TA,TS,UPFR,SA,CH2UD,CSTM,

1CKM,NAF,PREM,KDEX,RADL,REFE,VCAL,NXCH,PCTR,IM,NGCK,CFAM,NUP,

LSFIL,VEIL,LEHED,TAPE,UVFAL,VCFA,CCFA,MCFA,NCFL,

NUEA,TJSDU,CPFUS,CKKE,TREF,TLHE,TPFL,TRFL,TKLE,

1FMC,MCHE,RES,DESM,PMICF,PVPCL,UPLOQ,CPULDE,UTFH,4,

SMFIC,4,PKC41,UPF31,UGCHE,SA,DICF,ACIN,CA,CFN,FRP,FRK,

MAV,NUM,BALANCE

IF(NVAC.EQ.0)

RETURN
CONTINUE

GO TO 19

GO TO 20

CONTINUE

GO TO 31

CONTINUE

GO TO 32

CONTINUE

GO TO 600

MASS BALANCES

VOLUMETRIC FLOW RATE (LITERS/DAY)

144

146

148

150

152

154

156

158

160

162

164

166

168

170

172
IF MANURE=FLOW RATE THEN RECIRCULATION WATER IS NEEDED 00002600
THE 010 IS USED TO ACCOUNT FOR A CUMULATIVE MOUND-OFF EMON
00002640
*********************************************************************************
173
** IF(FY-FLW).LE.1.) GO TO 300
*********************************************************************************
174
** IF(FY-FLW).LE.1.) GO TO 300
*********************************************************************************
ọng
** IF MAKE UP WATER IS NEEDED BUT RECYLE IS NEEDED THEN GO TO 200
*********************************************************************************
175
** MAKE UP WATER IS NEEDED OPERATE AT MAX RECYLE AND ADD
*********************************************************************************
176
** IF(AA.GT.MS) GO TO 400
*********************************************************************************
177
** BLEED(LITERS/DAY)
*********************************************************************************
178
** BLEED=FY-REC-FILT/1000.
GO TO 500
*********************************************************************************
179
** WHEN INCOMING MANURE IS THE TOTAL INLET FLOW,
*********************************************************************************
180
** RECYLE(LITERS/DAY)
*********************************************************************************
181
*********************************************************************************
182
*********************************************************************************
183
*********************************************************************************
184
*********************************************************************************
185
*********************************************************************************
186
*********************************************************************************
187
*********************************************************************************
188
*********************************************************************************
189
*********************************************************************************
190
*********************************************************************************
191
*********************************************************************************
192
*********************************************************************************
193
*********************************************************************************
194
*********************************************************************************
195
*********************************************************************************
196
*********************************************************************************
197
*********************************************************************************
198
*********************************************************************************
199
*********************************************************************************
200
SUBROUTINE CUST(J,T,HRT,SO,UGC,HNEED,WM,HPTOT,FV,V,GAS,H1N)

CALL CUST(J,T,HRT,SO,UGC,HNEED,WM,HPTOT,FV,V,GAS,H1N)

RETURN

*****

SUBROUTINE CUST(J,T,HRT,SO,UGC,HNEED,WM,HPTOT,FV,V,GAS,H1N)

CALL CUST(J,T,HRT,SO,UGC,HNEED,WM,HPTOT,FV,V,GAS,H1N)

RETURN

*****
CENTRIFUGE CUST

C

R 550

IF(NVAC.EQ.0.0) GO TO 39
CCE=0.32*00G*(FV**0.5)
CN TO 41
CCE=0.39
CONTINUE
CCE=0.36
CONTINUE
C

GAS LINE COMPRESSOR CUST

C

R 391

IF(NVAC.EQ.0.0) GO TO 42
CLAG=0.102*00D*(FV**0.011)
CN TO 43
C CONTINUE
CLAG=0
C

SLUDGE DRYING BED CUST

C

R 392

IF(NVAC.EQ.1.0) GO TO 42
CLAG=0.102*00D*(FV**0.011)
CN TO 43
C CONTINUE
CLAG=0
C

HEAT EXCHANGER CUST

C

R 393

C

R 394

C

R 395

C

R 396

C

R 397

C

R 398

C

R 399

C

R 400

C

R 401

C

R 402

C

R 403

C

R 404

C

R 405

C

R 406

C

R 407

C

R 408

C

R 409

C

R 410

C

R 411

C

R 412

C

R 413

C

R 414

C

R 415

C

R 416

C

R 417

C

R 418

C

R 419

C

R 420

C

4200

4000

3990

3980

3970

3960

3950

3940

3930

3920

3910

3900

3890

3880

3870

3860

3850

3800

2000

1000

0100

0000

1000

0100

0000

1000

2000

3000

4000

5000

6000

7000

8000

9000

10000

11000

12000

13000

14000
Determine Nitrogen Cost

\[ \text{SOLUN} = (\text{SH} + \text{SHFV}) \times (\text{TNEF} + \text{TLEF}) \times \text{FRN} \]

\[ \text{SOLUN} = (\text{SOLUN} \times 1000) / ((\text{SH} + \text{SHFV}) + (\text{SHFV} \times \text{R})) \]

Determine Potassium Cost

\[ \text{SOLUK} = (\text{SH} + \text{SHFV}) \times (\text{TPEF} - \text{TLEF}) / (\text{TPEF} \times \text{FRK}) \]

\[ \text{SOLUK} = (\text{SOLUK} \times 1000) / ((\text{SH} + \text{SHFV}) + (\text{SHFV} \times \text{R})) \]

Determine Phosphorus Cost

\[ \text{SOLUP} = (\text{SH} + \text{SHFV}) \times (\text{TPEP} - \text{TLEP}) \]

\[ \text{ADUPADLSP} = \text{SOLUP} \times \text{CP205} \]

\[ \text{CP205} = \text{ADUPADLSP} \]

\[ \text{CFERT} = (\text{CNIT} \times \text{CP205}) \times 365 \]

Annual Water Cost

\[ \text{H2O} = 0.002 \times \text{GM} \]

Annual Steam Cost

\[ \text{IFINGA} = 0.01 \times \text{GM} \]

102

\[ \text{STDMP} = 0.00329 \times \text{IFINGA} \times \text{CSTM} \]

Annual Electric Power Cost

\[ \text{ELEC} = 0.029 \times \text{CSTM} \]

Go To 103

\[ \text{STDMP} = 0.00329 \times \text{CSTM} \]

Annual Utilities Cost

\[ \text{TOUTU} = 0.029 \times \text{GM} \]

Annual Labor Cost

\[ \text{PLPLT} = 0.03 \times \text{GM} \]

Annual Maintenance Labor Cost

\[ \text{RELAL} = 0.01 \times \text{GM} \]

Annual Total Labor Cost

\[ \text{TOAD} = \text{PLPLT} \times \text{RELAL} \]

Annual Administrative Overhead Cost

\[ \text{ADJU} = 0.01 \times \text{TOAD} \]

Annual Supplies Cost

\[ \text{UPSPL} = 0.03 \times \text{TOAD} \]

Annual Maintenance Supply Cost

\[ \text{MSP} = 0.015 \times \text{TOAD} \]

Total Annual Supplies Cost

\[ \text{TCP} = \text{UPSPL} + \text{MSP} \]

Annual Taxes and Insurance Cost

\[ \text{TAX} = 0.1 \times \text{TOAD} \]

Annual Total Gross Operating Cost

\[ \text{TGPO} = \text{TOUTU} + \text{TOAD} + \text{MSP} + \text{TCP} + \text{TAX} \]

Operating Costs For Fertilizer Plant

\[ \text{TLBH} = 0.3 \times \text{TOAD} \]

Annual Total GFOC Credit

\[ \text{CFERT} = \text{TLBH} \]

Go To 9009

\[ \text{TCD} = \text{IFC} \]

Annual Total GFOC Credit

\[ \text{TCD} = \text{IFC} \]

Go To 735

\[ \text{CRED} = \text{IFC} \]

Continue Determining Credit For CO2 If Herb or Temperature Are In Proper Limits

\[ \text{IFC} = \text{IFC} \]

Go To 735

\[ \text{CRED} = \text{IFC} \]

Continue Determining Credit For CO2 If Herb and Temperature Are In Proper Limits

\[ \text{IFC} = \text{IFC} \]

Go To 735

\[ \text{CRED} = \text{IFC} \]
473 9005 IF(TL<.40) GO TO 9060
474 9006 CUD(=MTGAS*GFCU2)/GFCH41
475 9007 CU0DU(=MTGAS*GFCU2)/GFCH42
476 9010 IFCEL(+.160) GO TO 9100
477 9011 CREDIE(=CREDIE+.54)
478 9100 IFUCPU=U1/GFCU2-CU2=GRCR
479 9102 IF(UCPU=U1/GFCU2-CU2=GRCR)
480 9103 TOTAL CAPITAL REQUIREMENTS FOR PLANT
481 9104 C START UP COST
482 9105 C MARKING CAPITAL COST
483 9106 WC=K+U2*TCPD
484 9107 C TOTAL CAPITAL REQUIREMENT
485 9108 TCAPU=TCPD+PREM+TCPD+KCPD
486 9109 C CALCULATIONS ON TOTAL COSTS/100 CU.FT. METHANE
487 9110 HENTZ=FRONT*PREM+(1.-FRONT)*KRETEU
488 9111 C DEPRECIATION
489 9112 DPRICE=0.05*(TCAPU-KCPD)
490 9113 CRETURN ON NET BASE
491 9114 C TANDED INCOME TAX
492 9115 C DETERMINE NET ANNUAL PROFIT
493 9116 IF(UGC.TL.0.) GO TO 657
494 9117 PCHR=GETYN(1.+0.99*UGC)
495 9118 CONTINUE
496 9119 C UNIT GAS COST
497 9120 C RETURN ON NET BASE
498 9121 C TANDED INCOME TAX
499 9122 C DETERMINE NET ANNUAL PROFIT
500 9123 IF(UGC.TL.0.) GO TO 657
501 9124 PCHR=GETYN(1.+0.99*UGC)
502 9125 CONTINUE
503 9126 C TANKER UNP/FEFAC
504 9127 CONTINUE
505 9128 WRITE(6,161)UGC,TI,HR1,SO,SB,ASYM,HNED,NM,HPTUT,REC,V,PNUM
506 9129 CONTINUE
507 9130 FORMAT(TI,ZP.2,4,4,F4.1,3,4,F4.1,2,4,F4.1)
508 9131 CONTINUE
509 9132 C TOTAL CAPITAL PLANT INVESTMENT
510 9133 1 IN DOLLARS
511 9134 2 IN FRENCH
512 9135 3 IN JAPANESE
513 9136 4 IN ENGLISH
514 9137 5 IN UNITS
515 9138 6 IN CURRENCY
516 9139 7 IN MILES
517 9140 8 IN LITERS
518 9141 C TOTAL PLANT INVESTMENT
519 9205 1 CREDIE
520 9206 2 CREDIE
521 9207 3 CREDIE
522 9208 4 CREDIE
523 9209 5 CREDIE
524 9210 6 CREDIE
525 9211 7 CREDIE
526 9212 8 CREDIE
527 9213 9 CREDIE
528 9214 0 CREDIE
529 9215 1 CREDIE
530 9216 2 CREDIE
531 9217 3 CREDIE
532 9218 4 CREDIE
533 9219 5 CREDIE
534 9220 6 CREDIE
535 9221 7 CREDIE
536 9222 8 CREDIE
537 9223 9 CREDIE
538 9224 0 CREDIE
Appendix IV. List of symbols and units used in modified computer programs.

| VARIABLE NAME | VARIABLE DEFINITION | UNIT |
|---------------|----------------------|------|}
| A             | HEAT EXCHANGE AREA   | sq. ft.|}
| B             | VACUUM FILTER AREA   | sq. ft.|}
| D             | DIGESTER SURFACE AREA | sq. ft.|}
| C             | ANNUAL ADMIN. OVERHEAD | $/DAY |}
| H             | DIGESTER AREA CAP. | sq. ft |}
| K             | METAL EXCHANGE AREA | sq. ft |}
| L             | BLEED STREAM         | gpm  |}
| M             | INITIAL VALUE OPTIMIZING |      |}
| N             | VOLUME LUMINATE OF SOLIDS |      |}
| O             | TOTAL CAPITAL INVEST | $     |}
| P             | CUMULATIVE EQU. MIN. | $/M-1 |}
| Q             | CUSH OF CERTIFIC. | $/M-1 |}
| R             | GAS COMPRESSION UNIT COST | $     |}
| S             | CREDIT FOR AMMONIA | $/TON |}
| T             | CUMULATIVE EQU. COST | $/M-1 |}
| U             | DEGRee COST         | $/M-1 |}
| V             | CONVENTIONAL DIGESTER COST | $/M-1 |}
| W             | PLASTIC DIGESTER COST | $/M-1 |}
| X             | COST TO SUPPLEMENT W/F | $/M-1 |}
| Y             | FERTILIZER PLANT INSURANCE | $/YR |}
| Z             | ANNUAL FEDERAL INCOME COST | $/YR |}
| AA            | FERTILIZER PLANT CAPITAL COST | $/PLANT |}
| BB            | REFEE VALUE         | $/TON |}
| CC            | WATER COST          | $/M-1 |}
| DD            | INSTRUMENTATION AND CONTROL COST | $/M-1 |}
| EE            | TOTAL COST FOR ADDING POTASSIUM | $/M-1 |}
| FF            | ELECTRICITY COST    | $/M-1 |}
| GG            | LAGUARD COST        | $/M-1 |}
| HH            | PRAKE COST          | $/M-1 |}
| II            | CUST OF N AS SUBSTYRED | $/M-1 |}
| JJ            | TOTAL COST FOR ADDING TETRONIDE | $/M-1 |}
| KK            | CUST OF CHLORINE | $/M-1 |}
| LL            | COMBINED FEE COSTS | $/M-1 |}
| MM            | ELECTRICITY COST    | $/M-1 |}
| NN            | TOTAL COST FOR ADDING PHOSPHATES | $/M-1 |}
| OO            | CREDIT FOR DIGESTER SOLIDS AS FERT. | $/M-1 |}
| PP            | CREDIT FOR FAN ELEC. | $/M-1 |}
| QQ            | RETURN OF BASE RATE | $/M-1 |}
| RR            | SLOPED COST         | $/M-1 |}
| SS            | CUST TO PRODUCE STEAM | $/M-1 |}
| TT            | CUST TO CONFINE CATTLE | $/M-1 |}
| UU            | STEAM CLST | $/M-1 |}
| VV            | VACUUM FILTERS COST | $/M-1 |}
| WW            | MEAT EXCHANGE COST  | $/M-1 |}
| XX            | FRATIONAL AMOUNT OF WATER IN FEED | $/M-1 |}
| YY            | PIPE DIAMETER       | IN.  |}
| ZZ            | DIGESTER COST FACTOR | $/M-1 |}
| AB            | MINIMUM CHARGE FOR OPTIMIZATION VAR. | $/M-1 |}
| AC            | INITIAL CHARGE FOR OPTIMIZATION VAR. | $/M-1 |}
| AD            | PHOSPHATE LEVEL DESIGNED IN FERT. | $/M-1 |}
| AE            | NITROGEN LEVEL DESIGNED IN FERT. | $/M-1 |}
| AF            | ANNUAL OPTIMIZATION | $/M-1 |}
| AG            | AERABIC DIGESTION ACTIVATION ENERGY | $/M-1 |}
| AH            | ANNUAL ELECTRIC COST | $/M-1 |}
| AI            | ENGINEERING COST FACTOR | $/M-1 |}
| AJ            | PASTERING FRACTION FACTOR | $/M-1 |}
| AK            | SOLIDS CONDENSING STREAM FROM DERRAFING | $/M-1 |}
| AL            | DIGESTER LEAKAGE | $/M-1 |}
| AM            | FRONTAL UPWELLING | $/M-1 |}
| AN            | PERCENT UPWELLING | $/M-1 |}
| AO            | DIGESTER EFFLUENT STREAM | $/M-1 |}
| AP            | PHYLAL EFFLUENT STREAM | $/M-1 |}
| AQ            | DIGESTER FLOW | $/M-1 |}
| AR            | DIGESTER FLOW | $/M-1 |}
| AS            | DIGESTER FLOW | $/M-1 |}
| AT            | DIGESTER FLOW | $/M-1 |}
| AU            | DIGESTER FLOW | $/M-1 |}
| AV            | DIGESTER FLOW | $/M-1 |}
| AW            | DIGESTER FLOW | $/M-1 |}
| AX            | DIGESTER FLOW | $/M-1 |}
| AY            | DIGESTER FLOW | $/M-1 |}
| AZ            | DIGESTER FLOW | $/M-1 |}
| BA            | TOTAL GAS PRODUCTION | $/M-1 |}
| BB            | ANNUAL GAS PRODUCTION | $/M-1 |}
| BC            | CONVERSION FACTOR | $/M-1 |}
| BD            | GAS COMPRESSION PIPING COST | $/M-1 |}
Appendix V. Data Input Format For Modified Computer Program

The computer programs to determine digester performance and economics is presented in Appendices and contain PROGRAM MANE, SUBROUTINE HOJE (A Brute Force Iteration Routine), SUBROUTINE MODEL, and SUBROUTINE COST, respectively.

The input data are read into the program through PROGRAM MANE. The information on the data input cards is as follows:

CARD 1 - Read K

K is the number of cases to be examined. Each case consists of the following set of cards:

K is in Col. 1 to 3

CARD 2 - Read N, NOPT, NGCK

N is the number of variables to be optimized -

N = 3 for plug flow or CSTR
N = 4 for series of CSTR's
N is in Col. 1 to 3

NOPT is an index to determine whether or not the optimization routine will be used -

NOPT = 0, use optimization
NOPT = 1, no optimization
NOPT is in Col. 11 to 13

NGCK is an index to determine the usage of gas -

NGCK = 0, gas to interstate pipeline
NGCK = 1, gas used internally only
NGCK = 2, gas used internally, excess to interstate pipeline
NGCK is in Col 21 to 23

CARD 3 - Read XMIN, XMAX, DELTA, DELMI, BOLD for temp.

There are N cards of this type

XMIN is the minimum value of the variable to be used in the optimization routine Col 1 to 10; decimal between 8 and 9

XMAX is the maximum value of the variable to be used in the optimization routine Col. 11 to 20; decimal between 18 and 19

DELTA in the initial step change in the variable, Col. 21 to 30; decimal between 28 and 29

DELMI is the minimum step change of the variable, Col. 31 to 40; decimal between 38 and 39

BOLD is the initial value for the variable for the optimization routine, Col. 41 to 50 with decimal between 48 and 49

Note that the input cards in this group set the conditions for temperature (1st card), retention time (2nd card), concentration (3rd card).

CARD 4 - Read NVAC, NXCH, NRCT, NDIG, NCEL, NCTCC

These are indices which determine equipment options with regard to dewatering, heat exchange, reactor type, reactor construction, internal use of electricity, and cost to confine cattle, respectively.

NVAC = 0, No centrifuge

NVAC = 1, Use centrifuge

Col. 1 and 2

NXCH = 0, No heat exchange on effluent

NXCH = 1, Use heat exchange on effluent

Cols. 11 and 12
NRCT = 0, plug flow
NRCT = 1, CSTR
  Cols. 21 and 22
NDIG = 1, Conventional digester
NDIG = 2, Plastic digester
  Cols. 31 and 32
NCEL = 1, No credit for internal use of electricity
NCEL = 2, Credit for internal use of electricity
  Cols. 41 and 42
NCTCC = 1, No cost to confine cattle
NCTCC = 2, Cost to confine cattle
  Cols. 51 and 52

CARD 5 - Read HERDN, SH, FVS, D, X, R, XPMAX

HERDN is the number of animals, Cols. 1 to 10; decimal between 6 and 7

SH is the manure production, gms/day/animal, Cols. 11 to 20; decimal between 16 and 17

FVS is the volatile solids fraction of total solids, Cols. 21 to 30; decimal between 26 and 27

D is the fractional water content of manure, Cols. 31 to 40; decimal between 36 and 37

X is the fractional solids content in the filter cake, Cols. 41 to 50; decimal between 46 and 47

R is the fractional refractory volatile solids, Cols. 51 to 60; decimal between 56 and 57

XPMAX is the maximum allowable percent solids concentration,
Cols. 61 to 70; decimal between 66 and 67

CARD 6 - Read E, RKO, A

E is the Arrhenius activation energy (cal/mole) divided by the gas content, Cols. 1 to 10; decimal between 6 and 7; should be negative

RKO is the constant in the Arrhenius rate expression (days⁻¹), Cols. 11 to 20; decimal between 17 and 18

A is the ratio of gm COD per biodegradable volatile solids, Cols. 21 to 30; decimal between 26 and 27

CARD 7 - Read TW, TS, TM

These are temperatures (°C) of makeup water, surroundings, and manure, respectively. TW, Cols. 1 to 10; decimal between 8 and 9; TS, Cols. 11 to 20; decimal between 18 and 19; TM, Cols. 21 to 30; decimal between 28 and 29

CARD 8 - Read OPER, SAL

OPER is the total number of operators (e.g., 2 per shift would be 6 operators), Cols. 1 to 10; decimal between 4 and 5

SAL is the operator wage ($/hr), Cols. 11 to 20; decimal between 14 and 15

CARD 9 - Read CH2OD, CSTMD, CKWHD

These are utilities costs for makeup water ($/MGAL), steam ($/MMBTU), and electricity ($/KWH), respectively. CH2OD, Cols. 1 to 10; decimal between 2 and 3; CSTMD, Cols. 11 to 20; decimal between 12 and 13; CKWHD, Cols. 21 to 30; decimal between 22 and 23

CARD 10 - Read DCFAC, VCFAC, CCFAC, HCFAC, RCFAC

These are cost factors for digester, vacuum filter, gas com-
pressor, heat exchanger, and raw materials, respectively.

- **DCFAC**: Cols. 1 to 10; decimal between 5 and 6
- **VCFAC**: Cols. 11 to 20; decimal between 15 and 16
- **CCFAC**: Cols. 21 to 30; decimal between 25 and 26
- **HCFAC**: Cols. 31 to 40; decimal between 35 and 36
- **RCFAC**: Cols. 41 to 50; decimal between 45 and 46

**CARD 11** - Read XDEX, PREM, FRDBT, RETEQ, RAXRT

- **XDEX**: is a cost factor index (Marshall and Stevens), Cols. 1 to 10; decimal between 6 and 7
- **PREM**: is the fractional interest on debt, Cols. 11 to 20; decimal between 12 and 13
- **FRDBT**: is the fraction debt, Cols. 21 to 30; decimal between 22 and 23
- **RETEQ**: is the fractional return on equity, Cols. 31 to 40; decimal between 32 and 33
- **TAXRT**: is the fractional federal income tax rate, Cols. 41 to 50; decimal between 42 and 43

**CARD 12** - Read NCFER, FVFIL, CRFED

- **NCFER**: is an index to determine credits for the process
  - NCFER = 0, no credits
  - NCFER = 1, credit for solids equal to manure fertilizer value
  - NCFER = 2, credit for solids as refeed
    - Cols. 1 and 2, no decimal

- **FVFIL**: is the fractional feed value of the solids from the dewatering unit, Cols. 11 to 20; decimal between 16 and 17
CRFED is the value for refeed ($/ton)
Cols. 21 to 30; decimal between 26 and 27

CARD 13 - IFPLA, NATF, CNUREA, CNIDBU, CPP205 CKK20

IFPLA is an index for type of fertilizer plant, new or used
IFPLA = 0, No fertilizer plant - NCFER = 0 or 2 for this case
IFPLA = 1, used fertilizer plant
IFPLA = 2, new fertilizer plant
Cols. 1 to 5; no decimal

NATF is an index for nitrogen addition type
NATF = 0, urea
NATF = 1, isobutylenediurea
Cols. 1 to 10; no decimal

CNUREA is the cost of urea/g, Cols. 11 to 20; decimal between 14 and 15

CNIDBU is the cost of isobutylenediurea/g, Cols. 21 to 30; decimal between 24 and 25

CPP205 is the cost of P205/g, Cols. 31 to 40; decimal between 34 and 35

CKK20 is the cost of K20/g, Cols. 41 to 50; decimal between 44 and 45

CARD 14 - Statement for fertilizer plant, TNEF, TNLEF, TPEF, TPLEF, TKEF, TKLEF, DESK, DESP, DESN

TNEF = Total NH$_3$-N in effluent, MMN, Cols. 1 to 5; decimal between 4 and 5

TNLEF = Total NH$_3$-N in liquid effluent, MMN, Cols. 6 to 10;
decimal between 9 and 10

\[ \text{TPEF} = \text{Total P in effluent, g/L, Cols. 11 to 15; decimal between 14 and 15} \]

\[ \text{TPLEF} = \text{TOTAL P in liquid effluent, g/L, Cols. 16 to 20; decimal between 19 and 20} \]

\[ \text{TKEF} = \text{Total K in effluent, g/L, Cols. 21 to 25; decimal between 24 and 25} \]

\[ \text{TKLEF} = \text{Total K in liquid effluent, g/L, Cols. 26 to 30; decimal between 29 and 30} \]

\[ \text{DESK} = \text{K level desired in finished fertilizer, g/kg, Cols. 31 to 35; decimal between 34 and 35} \]

\[ \text{DESP} = \text{P level desired in finished fertilizer, g/kg, Cols. 36 to 40; decimal between 39 and 40} \]

\[ \text{DESN} = \text{N level desired in finished fertilizer, g/kg, Cols. 41 to 45; decimal between 44 and 45} \]

**CARD 15 - Statements for gas, PRICF, PRICCO, GFCO21, GFCO22, GFCH41, GFCH42, PRICKW**

\[ \text{PRICF} = \text{Current wholesale price for organic fertilizer, $/g, Cols. 1 to 10; decimal between 4 and 5} \]

\[ \text{PRICCO} = \text{Current wholesale price of } \text{CO}_2, \text{ $/ton, Cols. 11 to 20; decimal between 14 and 15} \]

\[ \text{GFCO21} = \text{gram fraction of } \text{CO}_2 \text{ between 48 and 60°C, Cols. 21 to 30; decimal between 24 and 25} \]

\[ \text{GFCO22} = \text{gram fraction of } \text{CO}_2 \text{ between 25 and 42°C, Cols. 31 to 40; decimal between 34 and 35} \]

\[ \text{GFCH41} = \text{gram fraction of } \text{CH}_4 \text{ between 48 and 60°C, Cols. 41 to} \]
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GFCH42 = gram fraction of CH₄ between 25 and 42°C, Cols. 51 to 60; decimal between 54 and 55

PRICKW = price/KWHR paid by power company, $/KWHR, Cols. 61 to 70; decimal between 64 and 65

CARD 16 - Fertilizer plant costs, OPERF, OPCHEM, SALF, SALCH, CFINS,
OPERF = Number of fertilizer plant operations, Cols. 1 to 5; no decimal
OPCHEM = Number of chemists for fertilizer plant, Cols. 6 to 10; no decimal
SALF = Operators salary for fertilizer plant, $/hr, Cols. 11 to 15; decimal between 13 and 14
SALCH = Chemists salary for fertilizer plant, $/hr, Cols. 16 to 20; decimal between 18 and 19
CFINS = Cost for fertilizer plant insurance, Cols. 21 to 30; decimal between 28 and 29

CARD 17 - Fraction of NPK in digester solids, FRN, FRP, FRK
FRN = Fraction of mileage in digester solids, Cols. 1 to 10; decimal between 6 and 7
FRP = Fraction of phosphorus in digester solids, Cols. 11 to 20; decimal between 16 and 17
FRK = Fraction of potassium in digester solids, Cols. 21 to 30; decimal between 26 and 27

CARD 18 - Cost of raw manure, RMM,
RMM = Cost of raw manure, $/g, Cols. 1 to 10; decimal between 2 and 3
CARD 19 - PCFAC = Cost factor for plastic bag including pumps, Cols. 1 to 10; decimal between 8 and 9

CARD 20 - GCPIP = Cost for compression gas cost piping, Cols. 1 to 10; decimal between 8 and 9

SFMT = Cost of sewer for transporting manure, Cols. 11 to 20; decimal between 18 and 19

CARD 21 - PFACN = Pollution factor for nitrogen, Cols. 1 to 10; decimal between 5 and 6

PPFAC = Pollution factor for phosphorous, Cols. 11 to 20; decimal between 15 and 16

There are several restrictions on the use of these cards when certain options are selected. First, for NOPT = 1 (i.e., no optimization routine) CARD 3 must list the desired temperature, retention time, concentration, and number of digesters for the calculation in the BOLD position. The other values on this card are irrelevant.

For NGCK = 1 (gas used internally) the second of CARDS 3 for retention time must have XMIN = XMAX = BOLD. The actual value is irrelevant. The value of GFARM is irrelevant when NGCK = 0.


