ENGINEERING DESIGN CONSIDERATIONS
FOR METHANE FERMENTATION OF ENERGY CROPS

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SUMMARY

A simple "dry methane fermentation" process was developed in previous studies for the conversion of wheat straw and cornstalks. This ongoing study extends this approach to energy crops such as sorghum and napier grass.

The goal is to define the fundamentals of digestion of energy crops so that an optimized conversion system can be developed. Emphasis in early experiments is focused on development of conversion kinetics and evaluation of factors that influence the rates and the efficiencies of the conversion processes.

Criteria for an "optimized" system include maximum net energy production and minimal chemical and microbial additions and post-harvest handling. Conventional wet digestion of these substrates requires retention times in excess of 100 days and appears to have practical limitations, including substrate flotation and separation. Multiple cycle digestion in high-solids batch reactors has achieved greater than 60 and 80 percent volatile solids conversion in less than 100 days for napier grass and sorghum, respectively (at temperatures of 35°C and 55°C).

INTRODUCTION

The production of a high-yielding terrestrial crop that could be efficiently converted to substitute natural gas could generate a gross income greater than $2,000 per hectare per year. Diminishing supplies of natural gas and the need for alternative crops to provide a stable and expanding agriculture make this alternative interesting. This is the first report developed by the Cornell
University research team that is part of a national effort to develop future energy supplies from terrestrial biomass sponsored by the Gas Research Institute.

The goal of this research program is to develop a low-cost, simple, and efficient conversion process for terrestrial crops to biogas. The target of this effort is to identify the engineering design requirements for such a process to achieve methane production at a cost of $6.00 per GJ (in 1981 dollars). This paper presents initial results of a multiyear effort.

BACKGROUND

The use of terrestrial crops for energy production would include the use of crop residues such as corn stover, wheat straw, as well as plants specifically developed for energy production. A review of the entire system for photosynthetic carbon fixation on land as an alternative for energy production includes a wide variety of variables. Many crops can be eliminated due to lack of efficiency or incompatibility with an energy production system. For example, the millions of tons of wheat straw and corn stover left on fields represent a significant energy source. However, it is difficult to economically collect, transport, and utilize this dispersed material which is produced at less than six metric tons per hectare. A review of higher yielding crops has identified two which are being examined in our program—sorghum (grain and sweet varieties) and napier grass or elephant grass. Biomass yields for sorghum have led to the conclusion that this plant has a significant energy production potential (1). The reintroduction of sorghum in agriculture in the southeast has resulted in annual production of over five million hectares.

Four alternative systems for biogas production from high solids organics can be envisioned: 1) conventional process—using conventional wet anaerobic digestion in completely-mixed digesters using reactor solids concentration of between 5 and 10 percent solids by wet weight; 2) solid state fermentation—methane production in a solid state reactor using crops in a baled or field-prepared form. This system requires careful water management and reactor design to ensure optimal conversion of readily soluble organics; 3) leaching system with control of methane and hydrolysis reactions in the crop residues—Isolation of the hydrolysis reaction from the methane fermentation reaction to enable solubilization of the crop materials and transfer to a high rate reactor; or 4) combination solid state reactor with a soluble conversion step or combination of 2 and 3 above.

Although there is a great deal of information available on anaerobic digestion of organic matter, there is relatively little information available for the application of the process to terrestrial crops. The major variables in the process are water content, temperature, nutrient requirements, biomass densities and rheology, inoculant requirements and the relationship of the kinetics of conversion to substrate composition. A comprehensive two-year effort by a Cornell University team resulted in the identification of a simple process for the conversion of crop residues, i.e., wheat straw and corn stover (2). The process was referred to as "dry fermentation" because it worked in the absence of free or drainable water. Both the reaction rates and the efficiency of the system were unaffected at total initial solids concentrations of less than 25 percent (3) and a large scale-up of this to 110 cubic meters confirmed the commercial potential of such a system (4). A mass balance showed efficient recovery of the biodegradable carbon within 180 days.
All work with the dry fermentation process indicated that the final solids content was 17 to 20 percent regardless of the initial solids content of the system. This observation, confirmed with a prototype, indicated that imposing severe high solids requirements for initiation of methane formation created unnecessary problems that could be avoided by starting the reactor with more water. Water management with initial flooding of packed reactors would still enable a solid, relatively dry effluent to be obtained from these reactors. Thus the term "dry fermentation" is no longer used and all work with the energy crops has focused on reaction initiation with large quantities of water added to high solids batch reactors.

EXPERIMENTAL APPROACH

The overall objective of the experimental program is to identify a simplified anaerobic digestion system that eliminates input requirements (nutrients, inoculum, buffer chemicals) and results in equal or increased efficiencies over that achieved in completely-mixed systems.

The experimental program is limited to laboratory-scale efforts until early 1985, at which time pilots will be considered, with a prototype under consideration for 1986. It should be emphasized that this paper contains preliminary directions as determined from several years of studies with crop residues and only relatively short test periods with the promising energy crops. Theoretical discussions are included to indicate potential problem areas for the system.

In order to define the fundamentals of the organic interactions with an energy crop, it is necessary to be able to separate the hydrolysis kinetics from the biogas formation kinetics. Practical experiments to allow this separation should lead to definition of an optimized system for biogas production from energy crops. A two-stage reactor system was established to define these interactions. One 50-liter reactor was used for the long-term batch digestion of the crop, and a similar reactor was used to degrade the soluble organics leached from the batch crop reactor. Monitoring the liquid influents from each reactor as a portion of the liquid contents of one are recycled to the other enabled definition of hydrolysis rates, measurement of the onset of methane fermentation in the high solids batch reactor, and measurement of the biodegradability of soluble organics hydrolyzed and leached from the energy crops.

Multiple cycles were to be operated without the addition of alkalinity and nutrients after the first start-up to enable definition of the environmental requirements of the batch crop reactors. Three cycles of sorghum are nearly complete at both 35°C and 55°C operating temperatures. One cycle at 25°, 35°, and 55°C has been completed with napier grass.

Basic fundamentals are being examined in order to understand the limitations of anaerobic digestion as applied to high-yielding energy crops. Kinetics of biogas production at 25°, 35°, and 55°C are being developed in conventional completely-stirred wet reactors. It is not anticipated that the conventional process will be a competitive alternative, but it is necessary to operate units to confirm the digestion kinetics and other requirements for the process.
RESULTS AND THEORETICAL CONSIDERATIONS

Conventional Wet System Kinetics and Associated Problems

Digestion kinetics with napier grass and sorghum using 10-liter reactors maintained at between 10 and 12 percent dry matter are shown in Figure 1. Napier grass digestion has progressed smoothly with few problems. However, several loading rates with the sorghum have resulted in failure. Efforts to identify the inhibiting factor(s) are continuing. Operation of the units at lower loading rates have recently resulted in more stable reactions.

The relationship between a first order decay rate of the organic material in a completely-mixed digester and the retention time required to efficiently convert substrates to biogas is shown in Figure 2. Sorghum conversion was surprisingly slow at all temperatures in the conventional, completely-mixed reactors and was approximately equal to the maximum removal rates of wheat straw (3) and dry fermentation of cow manure (6). The slow reaction rates emphasize that a completely-mixed wet digester with hydraulic retention times substantially longer than 100 days would be required to convert over 80% of the biodegradable organic carbon.

Solid State Fermentation

Initiation of a successful start-up with a high solids batch reactor requires close control over the inoculum, buffer, pH and available nutrients. Because of the batch conditions, it is essential that a large population of methane forming bacteria be available to utilize the solubilized volatile acids formed in the first stages of anaerobic digestion. A reactor failure will occur when the formation of volatile acids exceeds the buffering capacity and the rate of methane formation. Thus it is easier to initiate a successful biogas start-up in a solid state batch reactor with substrates that have limited amounts of available soluble organics. Dry fermentation of wheat straw with a small inoculum addition was possible because of the relatively small amount of readily solubilized organics.

One requirement of an energy crop would be that it be highly biodegradable. In addition, preliminary consideration of storage requirements for the energy crop indicates that large accumulations of organic acids will be present at start-up. Initial experiments with sorghum indicated that 20 percent of the dry weight of field-dried sorghum was immediately available as soluble organics. In order to define the rate of removal that physical leaching could achieve as well as the stage at which available organics could be utilized by methanogens, the two-stage system described in the earlier section is being utilized. Recirculation of leachate to a liquid digester and then recycle of the treated leachate to the crop digester should lead to the definition of both hydrolysis and methane formation kinetics. It will also define the ease of separation of phases or control of one or both phases in various design options.

An example start-up of a sorghum reactor under mesophilic conditions is shown in Figure 3 and contrasted to the second cycle start-up. By achieving more efficient separation of the leachate, the second cycle start-up was much more rapid. Biogas production with approximately 50% methane was achieved after 30 days in the first cycle, 16 days in the second cycle, and 17 days in the third cycle with sorghum at mesophilic conditions. This indicates that rapid start-up and control of these kinds of reactors will be feasible.
Figure 1. Kinetics of anaerobic digestion of conventional completely mixed reactors with napier grass at 35°C (right) and sorghum at 55°C (left).
Figure 2. Theoretical relationship between organic removal rates, solids conversion efficiency, and completely mixed reactor hydraulic retention time assuming the following: the dry matter has an ash content of 11 percent of the dry weight; 90 percent of the volatile solids are biodegradable; the ratio of COD/TVS is 1.10; the digester is maintained at 12 percent total dry solids, and the kinetics are first order. Values shown are first order decay rate coefficients day$^{-1}$. Wheat straw and sorghum have maximum $k$ values of about 0.02 day$^{-1}$. 
Figure 3. Comparison of organic removals in high solids batch reactors with sorghum at 35°C in multiple cycles.
Mass balances on sorghum reactors indicate that the total volatile solids conversion efficiency has exceeded 80 percent in the long-term batch solid state reactors at 35°C and 55°C. This same efficiency appears to be achievable at 25°C. After 125 days the first 25°C cycle continues to produce gas at an equivalent volumetric rate of 0.08 volumes per volume per day. Although it is too early to make a conclusion, it would appear that the microbial system is gradually improving and that the efficiencies of the conversion process and the control of the soluble organics are improving. Most of the soluble organics are easily converted by the anaerobic contact process which is being used to treat the leachate from the high solids batch reactor. No buffer, inoculum, or nutrients have been added since starting the first cycle.

Environmental Effects and Requirements

Compaction and Density Problems. Most simplified applications of the digestion process to energy crops would utilize ensiled storage combined with anaerobic digestion. Such an approach should minimize the capital costs of the fermentation system. However, there is a potential problem in relation to the biological fermentation when the storage characteristics and dry densities of the substrates that will occur in a compacted ensiled form are considered. Reports of the dry matter densities in silage storage systems range from low values of 150 kg per cubic meter up to 350 kg per cubic meter (7). Examination of the compaction forces and dry matter content indicates that dry matter may be present in greater than 30 percent solids in these units. In other words, the compression forces achieved in deeper silos change the available water to such an extent that the biological reaction may be adversely affected. The interactions as extrapolated from silage references (7,8) and Wujcik's data on methane fermentation (3,6) are shown in Figure 4. These references are extrapolated and synthesized in Figure 5 correlating the significant dry weight changes that occur in silage and the resulting impact that may occur with methane fermentation. The commonly observed dry matter contents in ensiled materials may eliminate the possibility of methane fermentation. It also suggests a serious limitation for water management in such systems.

Nutrient Requirements. In an initial test conducted to determine the nitrogen content in the grain sorghum used in our program, 1.1 percent of the total dry weight was found to be nitrogen. Although such a low nitrogen content is attractive from a plant production standpoint, it may create problems with the digestion process itself (Figure 6). Microbial yield and the nitrogen requirements of microbes can be used to calculate the nutrient requirements for anaerobic digestion of crop residues. Figure 6 correlates the anaerobic digestion nitrogen requirement to the nitrogen content of a highly biodegradable plant. This can also be an indicator of other requirements that may be needed in digestion of energy crops. Nitrogen addition will be required for successful digester operation when it drops below about 1.6 percent of the dry weight of the substrate when the organic matter is 80 percent biodegradable.

Potential Full-Scale Energy Crop Digestion System. Although there is too little information to provide guidance for the design of an optimized digestion system, the information obtained to date enables a full-scale system to be approximated. The materials flow and the sizes of a full-scale system to produce one million cubic feet of methane per day are shown in Figure 7. This system is similar to option 4 mentioned in the Introduction.
Figure 4. Theoretical relationship between ensiled biomass storage depth and density, and biological conversion rates as extrapolated from references 5, 7, and 8.
Figure 6. Nitrogen requirements for anaerobic digestion of sorghum with the following characteristics: 80 percent of the organic matter is biodegradable, and the nitrogen content is varied from 0.3 to 3 percent of the dry weight.
Figure 7. Approximate materials flow (upper values in metric tonnes (dry) per year) and reactor size requirements (low figure) for a 28,000 m³/d (1 million ft³/d) methane generation facility using sorghum.
DISCUSSION

The general approach of this research program assumes that the conventional wet control digestion technology is not a viable alternative. In general, the research conducted to date confirms this. Wet control reactors would appear to be unmanageable since extensive separation and rheological problems occur while operating at dilute concentrations with most crop materials. Also, the wet reactors appear to be unstable and are adversely affected by small environmental changes. The rate of gas production does not appear to be substantially greater than that potentially achievable with the solid state fermentors. Thus, the wet control reactors are not considered to be an alternative for a full-scale energy crop digestion system.

Conversion of greater than 80 percent of the volatile solids of the sorghum achieved in this effort is encouraging from an energy standpoint. Efficient organic carbon conversion without pretreatment and without the addition of buffer or inoculum leads to the potential of inexpensive methane production possibilities.

Although much more information is necessary before an optimized reactor can be reliably designed, the information leading to the hypothesized system (Figure 7) would result in interesting economic potential. The total capital cost of the facility shown in Figure 7 would be approximately $4 million. The annual gross value of the energy provides about $2 million in income.

There are a number of substantial problems remaining to be defined with the system. The first general area relates to the integration of harvesting, storage and methane fermentation. Typical losses that occur in ensiled storage on farms vary between 10 and 20 percent of the organic matter (8). This is an unacceptably high loss, and more efficient methods of storage would be required for an energy facility. Documentation of the rate of loss of organic carbon upon harvesting and transportation to the central site and processing for storage must be efficient. This is an area that needs immediate attention. The second general concern relates storage effects to methane production. It would appear that this is an important area that may have been overlooked to date because the ramifications can only be determined in a full-scale system and will not be reflected in most laboratory-scale experiments.

In summary, although a great deal of research remains, practical laboratory-scale experiments have shown that an energy crop candidate capable of large yields can be efficiently converted to biogas with minimum reactor control requirements.

REFERENCES CITED


