0273-2289/89/2021—0587$03.20

Biogasification of Community-Derived Biomass and Solid Wastes in a Pilot-Scale SOLCON® Reactor

VIPUL J. SRIVASTAVA,[1,*] RICHARD BILJETINA,[1] H. RONALD ISAACSON,[2] AND THOMAS D. HAYES[2]

[1]*Institute of Gas Technology, Chicago, IL 60616; and*
[2]*Gas Research Institute, Chicago, IL 60631*

ABSTRACT

The Institute of Gas Technology has developed a novel, solids-concentrating (SOLCON®) bioreactor to convert a variety of individual or mixed feedstocks (biomass and wastes) to methane at higher rates and efficiencies than those obtained from conventional high-rate anaerobic digesters. The biogasification studies are being conducted in a pilot-scale experimental test unit (ETU) located in the Walt Disney World Resort Complex, Orlando, FL.

This paper describes the ETU facility, the logistics of feedstock integration, the SOLCON reactor design and operating techniques, and the results obtained during 4 y of stable, uninterrupted operation with different feedstocks.

The SOLCON reactor consistently outperformed the conventional stirred-tank reactor by 20% to 50%.

Index Entries: Biogasification; anaerobic digestion; biomass; municipal solid waste; methane.

INTRODUCTION

The Institute of Gas Technology is studying the biogasification of community wastes in an experimental test unit (ETU) located at the Community Waste Research Facility (CWRF) at the Walt Disney World Resort Complex in Florida. This project is part of a larger program designed to

*Author to whom all correspondence and reprint requests should be addressed.

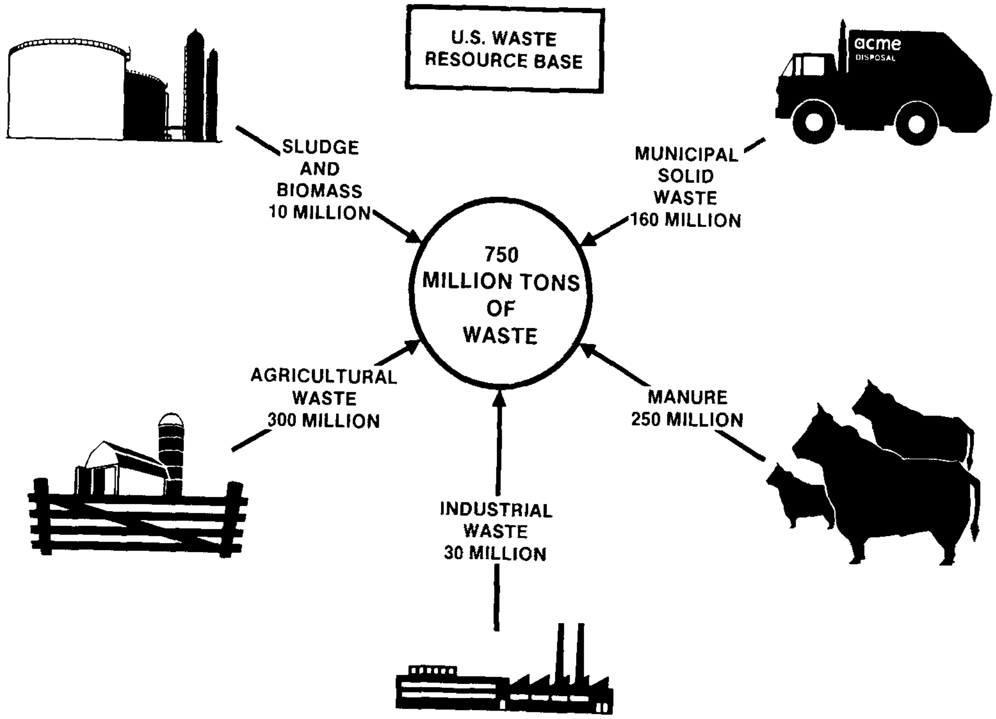


Fig. 1. Potential waste resource base in the US for a community and its surroundings (annual dry tons).

provide solutions to community waste treatment and disposal problems. Of primary importance to this program is the implementation of low-cost, nonenergy-intensive waste treatment technologies and the net production of energy (methane) from waste resources.

Five waste resource streams have been identified as potential energy production sources for a typical community and its surrounding areas (Fig. 1). They are sludge and biomass from wastewater treatment plants, municipal solid wastes, industrial wastes, agricultural wastes, and manure. Nationwide, these resources total about 750 million dry tons annually, and after conversion could add up to 5 EJ to the nation's energy supply (*1*).

The concept of waste treatment and subsequent methane production from these sources is being studied in a novel solids-concentrating anaerobic digester at the ETU facility designed, constructed, and operated by IGT. Operation of the ETU digester began in January 1984. During 1984 and 1985, tests were conducted on blends of water hyacinth and sludge in support of a process concept that provides effective secondary and tertiary wastewater treatment using aquatic macrophytes such as water hyacinths (*2*).

The system concept, illustrated in Fig. 2, employs water hyacinth ponds for secondary and tertiary treatment of effluent from a wastewater

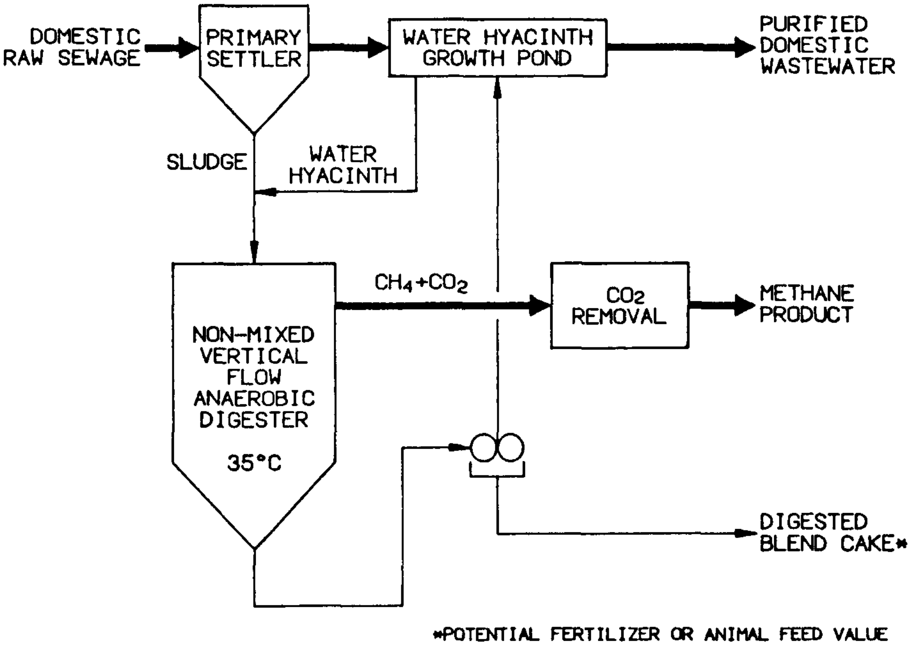


Fig. 2. Schematic diagram of integrated water hyacinth domestic wastewater treatment and digestion system.

treatment plant, which had been subjected to primary treatment (removal of settleable solids). Primary supernatant is passed through water hyacinth ponds for secondary and tertiary treatment (organic matter and nutrient reduction). The water hyacinths were harvested from five 1/4-acre treatment channels at the CWRF and were mixed with sludge from the primary clarifier. Blend ratios were maintained between 2:1 and 1:1 water hyacinth/sludge to simulate expected production quantities from larger commercial treatment facilities. Results from these tests demonstrate that, using a 4.5 – m^3 (1200-gallon) solids-concentrating anaerobic digester, water hyacinth and sludge blends can be converted to methane at higher rates and efficiencies than those for conventional stirred tank reactors (CSTR) (3). An economic assessment completed by an independent engineering firm has shown that a combined water hyacinth wastewater treatment and anaerobic digestion process results in the production of methane at $2.50 per GJ or less (4).

The second feedstock selected for testing at the ETU was an agricultural product, sorghum, because, as discussed earlier, one of the largest waste sources in the US is the agricultural sector. Its wastes represent over 1/3 of the 750 million dry tons, as identified in Fig. 1. In 1985, a total of 7.2 million hectares of sorghum were planted in the US; research at Texas A&M University indicated that yields up to 80 tons (fresh weight) of sorghum per hectare are possible for sweet sorghm (5,6). It is important, however, to develop suitable storage systems to enable year-round production of energy from such seasonal crops. During storage or ensilage, the sorghum undergoes an anaerobic fermentation that produces lactic, acetic, and butyric acids. The resultant drop in pH prevents further conversion of the sorghum.

In 1986, two 6-mo tests were conducted on sorghum. The first test was conducted with an ATX623XRIO sorghum at mesophilic conditions, and the second was conducted with an MN-1500 sorghum at thermophilic conditions. The ETU methane yields exceeded those of the sentinel CSTR by 50% and 20%, respectively (*7*).

The third feedstock selected for conversion studies was a refuse-derived fuel (RDF) fraction of municipal solid waste (MSW). A conservative estimate of MSW production in the US is approximately 160 million dry tons per year (Fig. 1). However, some researchers have estimated the MSW production to be approximately 220 million dry tons (*8*). Nevertheless, RDF represents a large waste resource, equivalent of up to 2 EJ of energy per year, for the US. The RDF for the ETU experiments was obtained from a resource recovery plant located in Baltimore, MD. This plant was chosen as a source because it is capable of delivering a 10×0 mm sized feed material to the ETU and eliminates the need for installation of additional sizing and separation equipment at the ETU. Only minor modifications were necessary to allow processing of 5–10 wt% RDF slurries in the ETU. A description of the ETU facility follows.

ETU Description

Figure 3 provides a schematic diagram of the ETU. The feed (chopped water hyacinth, ensiled sorghum, or RDF as received) is transported to the loading platform (A) of the ETU and fine-ground to a product size of 3 mm. In the case of sorghum and RDF, which are high in total solids, the ground feed is subsequently diluted with influent sewage to 5–10 wt% solids and stored in an insulated, cooled, enclosed tank (C) to preserve the inventory during the intermediate storage period. Groundwater hyacinth naturally has less than 10 wt% solids; therefore, it does not require any dilution. A mixer and pump recirculation are provided to guarantee uniform product delivery to the feed blending tank where ground feed (except sorghum) is mixed with the primary sludge. Equipment is sized to process a 3-d inventory in less than 1 h.

Influent sewage is made available from the feed line to the primary clarifiers at the resort's wastewater treatment plant. A grinding and pumping station is provided to chop any foreign materials (such as plastic or paper) to a product size less than 3 mm in diameter and to pump the sewage through an underground main to the ETU. An intermediate storage tank (D) is provided for sewage sludge.

The ground hyacinth, or RDF, and primary sludge is next pumped to a feedblend tank (E) in predetermined amounts so that the desired ratios of hyacinth and sludge or RDF and sludge are maintained. In the case of

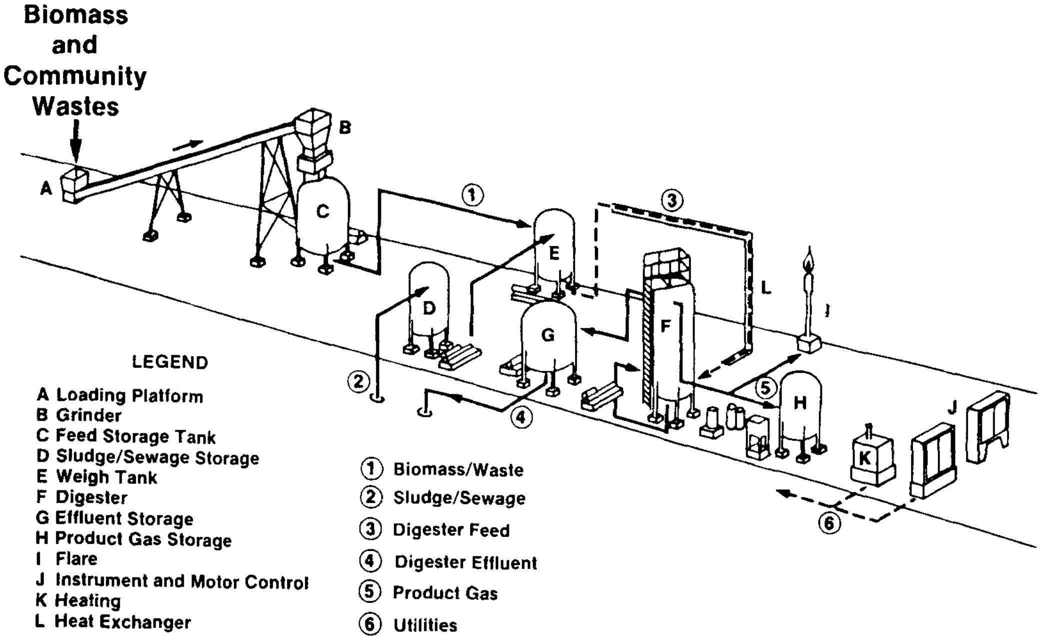
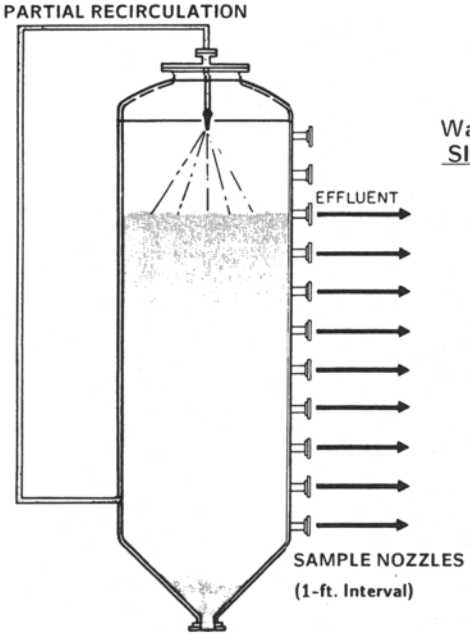


Fig. 3. Schematic of the experimental test facility.

sorghum, primary sludge is not added. This tank is mounted on a set of load cells to provide an accurate account of the feed slurry loading rate to the digester. A variable-speed, progressive-cavity pump and cycle timer allows feed to be added continuously or on an intermittent basis. A feed heat exchanger (L) automatically preheats the blend feed to minimize temperature fluctuations in the digester (F). The nominal feed rate to the digester is 790 wet kg/d (2000 wet lb/d) of diluted feed containing 5% solids. The feeding equipment can handle a wide range of feed rates and slurry concentrations.

Biogasification of sorghum occurs in a 4.5 – m^3 (1200-gallon) novel unmixed vertical-flow solids-concentrating (SOLCON®) digester (F) with a height-to-diameter ratio of 2:1. This design and operating mode promote the retention of microorganisms and to-be-reacted solids through passive settling. The digester is fully jacketed and insulated to allow automatic temperature control of the contents. Twelve thermocouples monitor internal temperatures, and sample ports are provided every 0.3 meter (1-ft) of vertical height. The system is capable of operation at both mesophilic and thermophilic conditions. A complete gas storage and handling system is provided. Continuous analysis for methane and carbon dioxide and measurement of the gas flow are provided prior to gas flaring. All pertinent data are continuously recorded on strip charts located in a main control panel.

The SOLCON digester can be operated in either an upflow mode (the feed injected at the bottom and the effluent removed from a port located



2.1 Water Hyacinth Sludge Blend	Sorghum	MSW
7.6	2.2	10.2
6.2	1.7	4.1
6.8	1.8	7.5
6.7	2.1	3.5
6.8	2.1	8.1
5.2	2.7	3.0
0.8	3.9	3.7
0.7	5.5	2.2
1.5	5.9	2.4

Fig. 4. Schematic diagram of the SOLCON digester in a downflow mode.

near the top of the digester) or in a downflow mode (the feed injected at the top of the digester and the effluent withdrawn from the bottom of the digester). Figure 4 is a schematic diagram of the SOLCON digester while operating in a downflow mode. The operation mode which promotes the settling of microorganisms and feed solids is selected for a particular feed for steady-state operation. In addition to the feed slurry rheology, feed solids behavior in the digester is used to select the mode of operation.

Both the water hyacinth and RDF have low specific gravities and have a tendency to float in the digester. Therefore, to increase the retention of the feed solids, the digester was operated in a downflow mode. In the case of sorghum, which tends to settle, the digester was operated in an upflow mode. This digester design differs from the upflow sludge blanket digester widely applied to the anaerobic digestion of soluble feeds in that the feed solids contain a higher concentration of nonhomogeneous particulate matter, and the bed, which is not expanded, contains unreacted solids and microorganisms. This reactor concept, as mentioned earlier, has been successfully applied to a relatively low-solids biomass (water hyacinth) in a downflow mode and a medium-solids biomass, sea kelp in an upflow mode (*3,9,10*).

Effluent from the digester can be removed automatically through an overflow system or by pump withdrawal from a number of locations. The digester effluent can be stored in a 4.5 – m^3 (1200-gallon) tank (G) to allow further processing, such as dewatering followed by liquid recycle to preserve nutrients, or returned to the plant clarifier. The effluent solids can be used as a source of fertilizer and/or animal feed.

The product gas is either stored in the gas storage tank (H) and then flared (I) or flared directly without storage. Either way, the volume and quality of gas produced is recorded continuously through strip chart recorders located at the control panels (J).

RESEARCH OBJECTIVES

The objective of the ETU tests was to demonstrate biogasification concepts for the production of methane from commercially-derived biomass and wastes and to obtain data for commercial scaleup. The specific objectives of this study were to validate baseline digester operation and performance data obtained in the laboratory and to evaluate larger scale equipment for feed preparation, transport, and other digestion-related unit operations. The design of the ETU facility incorporates a high degree of flexibility to allow testing with a number of different feedstocks and includes front-end feed processing and slurry preparation equipment, a cold-flow test column, a $4.5-m^3$ (1200-gal) SOLCON digester, digester effluent processing equipment, and gas handling equipment. Results obtained from the ETU provide the basis for complete conceptual process designs and cost estimates for process demonstration units.

ETU TESTS DURING 1984–1987

Operation of the ETU digester began in January 1984. Initial tests were conducted on blends of water hyacinth and sludge to support a process concept that provides effective secondary and tertiary wastewater treatment using aquatic macrophytes such as water hyacinths (2). Blend ratios were maintained between 2:1 and 1:1 water hyacinth/sludge to simulate expected production quantities from larger commercial treatment facilities. Anaerobic digestion was performed in an unmixed, solids concentrating (SOLCON) digester. No nutrient was added in the feed. Data were collected during six different performance periods over a 2-y period of uninterrupted digester operation (3).

After the test program on water hyacinth/sludge blends in 1985 was completed, preparations were made at the ETU to feed an agricultural product, sorghum. In 1986, two 6-mo tests were conducted on sorghum. The first test was conducted with an ATX623XRIO sorghum at mesophilic conditions, and the second was conducted with an MN-1500 sorghum at thermophilic conditions. Nutrients were added to maintain feed nutrient ratios for C/N, C/P, and C/S at 15, 100, and 150, respectively. (In a commercial operation, a nutrient balance would be achieved using effluent liquid recycle.)

The test program on RDF feed was initiated in late 1986. Potential solids distribution and slurry rheology during actual digestion was studied in a 7.5-meter (25-foot) high, 0.4-m^3 (1000-gal) cold-flow test column, installed in 1986. Such studies provide patterns of solids behavior in the digester. In 1987, two tests were conducted on RDF. The first test established a baseline performance of SOLCON with a 15:1 RDF/primary sludge blend with external nutrient supplementation to obtain the desired ratios for C/N, C/P, and C/S (15, 100, and 150, respectively). The second test was conducted with the same 15:1 RDF/sludge feed but with effluent supernate recycle. Owing to the lack of an appropriate mechanical dewatering unit at that time, only partial liquid recycle could be achieved. However, the data obtained were sufficient to prove that liquid recycle will eliminate the need for daily addition of nutrients when nutrient-deficient feed is used for digestion.

RESULTS AND DISCUSSION

Feed Characteristics

The four different feedstocks tested to date—water hyacinth, primary sludge, sorghum, and refuse-derived fuel (RDF)—were similar in chemical composition but very different in physical and biochemical properties. Table 1 is a summary of the physical, chemical, and biological characteristic data. Both primary sludge and water hyacinth were similar in nutrient levels and total and volatile solids contents, but their feed heating values and biologically recoverable energy were very different. Primary sludge was more digestible with 91% recovery under anaerobic conditions than the water hyacinth, which yielded only 60% recovery. Sorghum, as received, contained a high fraction of volatile solids (a low ash content) and was typical of land-based biomass in terms of energy value and recoverable energy level. It was low in nutrients (N, P, and S) and required supplementation. The RDF was very dry (less than 7% moisture), contained low levels of nutrients, and was the least digestible of the four feedstocks tested. RDF also required nutrients to sustain an uninhibited level of anaerobic digestion.

In addition, data were collected to determine the solids distribution pattern within the digester. Figure 5 provides the solids profiles obtained in the digester at similar loading rates for water hyacinth/sludge blends, sorghum, and RDF (a fraction of MSW). The water hyacinth/sludge blend and RDF tended to float, whereas the sorghum tended to settle. On the basis of these data and data on volatile acids and pH profiles within the digester, upflow operation is recommended for sorghum and downflow

Table 1
Physical, Chemical, and Biological Characteristics of ETU Feedstocks

	Primary Sludge	Hyacinth	Sorghum	MSW[a]
Feed type, as received				
Total solids, TS				
% wet wt	4.8	4.9	27.5	93.3
Volatile solids, VS				
% TS	83.6	82.9	93.8	91.1
Elements,				
% TS				
Carbon, C	47.1	40.7	44.4	41.9
Hydrogen, H	7.04	5.72	6.16	5.67
Nitrogen, N	3.75	3.02	1.15	0.59
Phosphorus, P	0.56	0.73	0.24	0.05
Sulfur, S	0.49	0.76	0.10	0.12
Nutrient ratios[b]				
C/N	13	13	39	71
C/P	84	56	190	840
C/S	96	54	440	350
Energy (heating) value				
kJ/kg VS	25,600	19,500	19,000	17,000
(Btu/lb VS)	(11,000)	(8,370)	(8,160)	(7,320)
Biologically recoverable energy in product gas[c]				
kJ/kg VS	23,300	11,600	14,000	9,300
(Btu/lb VS)	(10,000)	(5,000)	(6,000)	(4,000)
Recovery efficiency, %	91	60	74	55

[a]RDF fraction.
[b]Preferred C/N, C/P, and C/S ratios are 15, 100, and 150, respectively.
[c]As determined by anaerobic biogasification potential (ABP) assays (3). These data are accurate to within ±10%.

is recommended for water hyacinth/sludge blend and RDF for optimum digestion. During water hyacinth/sludge digestion, however, both upflow and downflow operations were employed to confirm the above observation. By operating the SOLCON digester in this fashion, thereby taking advantage of the natural properties of the particular feedstock, the solids retention time could be easily increased without increasing the hydraulic retention time and, correspondingly, without increasing the reactor volume. These solids distribution patterns were not readily observed in laboratory-scale digesters, therefore, stressing the importance of following a logical progression of scaleup toward commercial operations.

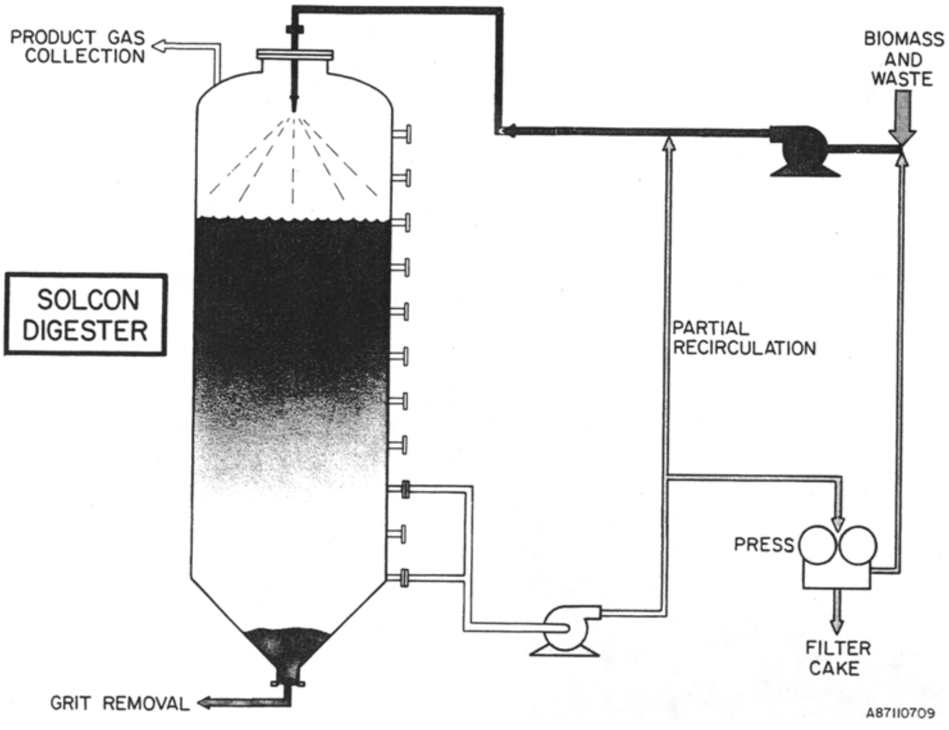


Fig. 5. Solids profiles in the digester for various feedstocks at similar loading rates (0.2/lb VS/ft^3-d) and HRTs (11–13 d) measured in weight percent total solids.

SOLCON Digester Performance

Digestion experiments with SOLCON were conducted with water hyacinth/sludge blends, sorghum, and RDF. To assess the advantages of SOLCON digester over a continuously stirred tank reactor (CSTR) in terms of improved digestion efficiencies, a 50-L CSTR was operated simultaneously at the same operating conditions, receiving exactly the same feed.

The performance data for the digesters (Tables 2, 3, and 4) are presented on the basis of per-unit weight (kg) of volatile solids (VS) added and per-unit weight (kg) of organic matter added. This was done because feed slurries always contained appreciable quantities of fatty acids, and sometimes ethanol as well. The presence of ethanol and/or fatty acids introduces errors in the determination of solids or chemical oxygen demand (COD) using standard procedures (3). The method for determining solids concentration assumes that the weight loss during drying is only caused by evaporation of water from the sample and that the dried residue contains all of the sample organic (VS) and inorganic (ash) components. The volatile

Table 2
SOLCON Digester Tests with Water Hyacinth/Sludge Blends, WH/SL

Test no.	1	2	3	4	5	6
Duration, months	5	3	3	4	1	3
Steady-state period, wk	4	3	4	4	4	4
Operating mode, flow	Up	Up	Down	Down	Down	Down
Blend ratio, WH/SL	2:1	1:1	1:1	2:1	2:1	2:1
Average feed solids content, wt%	4.5	3.6	3.8	3.7	3.8	4.4
Temperature, °C	35	35	35	35	35	35
Loading rate						
kg VS/m^3-d	3.2	3.2	3.2	3.2	3.2	4.8
kg org. matter/m^3-d[a]	3.5	3.4	3.5	3.6	3.5	5.5
HRT, days	12	11	11	11	10	7
SOLCON methane yield m^3 kg VS added	0.28[b]	0.43	0.49	0.41	0.37	0.30
SOLCON methane production rate vol/vol-cult.-d	0.9	1.3	1.5	1.3	1.2	1.5
SOLCON methane yield m^3/kg-organic matter added[a]	0.26	0.40	0.45	0.36	0.34	0.26
SOLCON effluent solids content, wt%	3.0	2.0	1.9	2.5	2.4	2.6
SOLCON Effluent, pH	7.3	7.2	7.2	7.3	7.3	7.1
SOLCON carbon balance, %	98	105	103	108	99	94
CSTR methane yield m^3/kg-organic matter added[a]	0.22	0.36	0.41	0.27	0.27	0.24

[a] Organic matter is defined as the volatile solids determined by using standard methods plus volatile acids that get evaporated (lost) during solids determination. This loss was experimentally determined.

[b] Digester experienced some mechanical problems during this period. Methane yield was not optimized.

fatty acids and ethanol have relatively low boiling points (78–190°C); thus, a significant degree of evaporation of these compounds is expected at the temperature used for drying. A similar loss is believed to occur because of volatilization of straight-chain aliphatic compounds into the headspace of the digestion flask during COD analyses (*11*). Such losses of organic compounds would result in lower than actual loading rate values and higher than actual total gas and methane yield values.

To overcome the limitations of the analytical procedure for solids determination, actual fatty acids and ethanol losses were determined for each feed slurry. The average losses were then used as a basis for calculating the total organic matter concentration of feed slurries, defined as the sum of the analyzed volatile solids and the organic compound losses. Therefore, the digester operating conditions and performance data were

Table 3
Digester Tests with Ensiled Sorghum

Test no.	1	2
Sorghum type	ATX623XRIO	MN-1500
Duration, months	6	6
Steady-state period, weeks	4	4
Operating mode, flow	Up	Up
Average feed solids content, wt%	5.0	7.6
Temperature, °C	34	56
Loading rate		
kg VS/m^3-d	3.4	5.9
kg org. matter/m^3-d[a]	4.3	7.5
HRT, d	13	10
SOLCON methane yield m^3 kg VS added	0.43	0.34[b]
SOLCON methane production rate vol/vol-cult.-d	1.4	2.0
SOLCON methane yield m^3/kg-organic matter[a]	0.33	0.27
SOLCON effluent solids content, wt%	2.2	4.5
SOLCON effluent, pH	7.0	7.3
SOLCON carbon balance, wt%	93	97
CSTR methane yield, m^3/kg-organic matter[a]	0.22	0.23

[a]Organic matter is defined as the volatile solids determined by using standard methods plus volatile acids that get evaporated (lost) during solids determination. This loss was experimentally determined.
[b]Methane yield was not optimized, as discussed in the text.

calculated on the basis of organic matter as well as volatile solids to provide the compatability of comparing data presented here with any other data that the reader may possess.

Water Hyacinth/Sludge Blend Digestion

The bioconversion of sludge and water hyacinth blends in the SOLCON digester was highly successful. Six tests were completed between July 1984 and December 1985. Performance data were collected initially in the upflow and later in the downflow mode of operation for water hyacinth/sludge blends of 2:1 and 1:1, respectively. Temperatures were maintained at mesophilic conditions (35°C), and loading rates were controlled at 3.2 kg VS/m^3-d (11-d hydraulic retention time) except for the last test, which was conducted at a loading rate of 4.8 kg VS/m^3-d (7-d hydraulic reten-

Table 4
Digester Tests with 15:1 RDF/Sludge

Test no.	1	2
Duration, months	5	5
Steady-state period, wk	5	5
Nutrient recycle	No	Yes
Operating mode, flow	Down	Down
Average feed solids content, wt%	7.1	7.8
SOLCON temperature, °C	35	35
Loading rate		
kg VS/m^3-d	3.2	3.2
kg org. matter/m^3-d[a]	3.5	3.4
HRT, d	17	18
SOLCON methane yield m^3 kg VS added	0.27	0.25
SOLCON methane production rate vol/vol-d	0.87	0.81
SOLCON methane yield m^3/kg-org. matter[a]	0.24	0.22
SOLCON effluent solids content, wt%	6.1	6.1
SOLCON effluent, pH	7.2	7.1
SOLCON organic matter balance, %	104	106
CSTR-1[b] methane yield m^3/kg org. matter[a]	0.19	0.18
CSTR-2[c] methane yield m^3/kg org. matter[a]	0.21	0.19

[a] Organic matter is defined as the volatile solids, determined by standard methods plus volatile acids that were lost during solids analyses. This loss was experimentally determined.
[b] Mesophilic temperature, 35°C, as in the case of the SOLCON digester.
[c] Thermophilic temperature, 55°C.

tion time). Operating during the entire test period was uninterrupted; no nutrient addition was necessary. The digester was not mixed to maximize the solids retention time. Partial recirculation maintained an active culture at the top of the digester. Gas yields as high as 0.77 m^3/kg VS and methane yields as high as 0.49 m^3/kg VS or 0.45 m^3/kg organic matter added were obtained using a 1:1 water hyacinth/sludge blend. This represents over 90% of the maximum expected biodegradable yield as measured by bioassays for the water hyacinth and sludge material.

Table 2 provides an overview of the test results. These data confirm that, for water hyacinth/sludge blends, the downflow mode, and an 11-d hydraulic retention time is the preferred method of operation in the SOL-

CON digester. Blend ratios of 2:1 water hyacinth/sludge have a lower yield than 1:1 ratios because the water hyacinth is less biodegradable than the sludge. However, in all cases, the SOLCON methane yields were up to 33% higher than those of the CSTR operated in the field receiving the same feed material.

Sorghum Digestion

In 1986, two tests were conducted on ensiled sorghum. The first test was conducted with the ATX623XRIO sorghum, which was ensiled for about 1 y. This test was conducted at mesophilic temperature (34°C) with approximately 5.0% solids concentration in the feed slurry. The second test was conducted with the MN-1500 sorghum, which was ensiled for about 4–8 w. This test was conducted at thermophilic temperature (56°C) with approximately 7.6% solids concentration in the feed slurry. High methane yields from both the SOLCON and the CSTR (Table 3) suggest that sorghum is a very biodegradable feed. Under mesophilic conditions, an average methane yield of 0.43 m^3/kg VS added was obtained at a loading rate of 3.4 kg of volatile solids/m^3-d. This represents a nearly complete conversion of the biodegradable portion of the sorghum. The SOLCON methane yield exceeded that of the CSTR by 50%.

At thermophilic conditions, methane yields of 0.34 m^3/kg volatile solids fed were obtained for a loading rate of 5.9 kg of volatile solids/m^3-d and methane production was increased from 1.4 to 2.0 vol/vol-cult-d (Table 3). With further optimization it may be possible to increase the methane yields even more at thermophilic conditions in the solids-concentrating digester. Although additional investigations on sorghum at thermophilic conditions are recommended, sufficient data were collected to allow scaleup of a solids-concentrating digester for the conversion of sorghum to methane. Operation once again was uninterrupted.

RDF Digestion

The test program on RDF feeds was initiated in late 1986. Solids distribution and slurry rheology were first studied in a 7.5-meter-high, 3.8 – m^3 cold-flow test column. As a result of these studies, modification of existing equipment was minimized and downflow operation was chosen for the RDF feed material in the digester. Data were collected during two performance periods. The first period established baseline conditions for a 15:1 RDF/primary sludge (PS) blend fed at a loading rate of 3.2 kg VS/m^3-d to the SOLCON digester operated at mesophilic conditions and a hydraulic retention time of 16 d. Dilution using raw sewage resulted in a feed solids concentration of about 7 wt% solids. Nutrients were added to maintain feed nutrient ratios for C/N, C/P, and C/S at 15:1, 100:1, and 150:1, respectively. No digester effluent was recycled. Commercial operation would eliminate nutrient addition by recycling the digester effluent. This was demonstrated in a second performance period, using partial effluent recycle to reduce the nutrient requirements while maintaining other operating parameters similar to those of performance period 1 (Test No. 1).

Once again, excellent conversions were obtained using RDF/sludge feedstock. The digester, operated at mesophilic conditions, achieved methane yields that exceeded yields from both the mesophilic and thermophilic CSTR digesters (*see* Table 4). The SOLCON digester produced methane yields of up to 0.27 m^3/kg volatile solids added, which is approximately 90% of the maximum biodegradable methane yield as measured by ABP bioassay. Also, during the second test, when part of the effluent was being recycled, the nutrient requirement dropped by over 60%, whereas the digester performance remained very similar to that when nutrients were being added during the first test.

SUMMARY

The data collected for three different feed materials tested at the pilot-scale ETU facility and other work conducted at IGT show that an unmixed, SOLCON digester consistently outperforms a conventional CSTR, operating on feed slurries containing 5–15 wt% solids. Methane yields have exceeded those of a CSTR digester in all cases by 20–50%. This type of digestion system is also extremely stable and flexible. Four years of uninterrupted operation have been logged in the digester. During that time feedstocks, loading rates, and temperatures were changed without the need to reinoculate a ''stuck'' digester. Transition periods for different feedstocks and loading rates have been very smooth. In summary, a SOLCON digester

- Does not require continuous mixing;
  - Reduces energy consumption;
- Promotes retention of solids;
  - Smaller digester;
  - Higher conversion rates and efficiencies;
- Has no internals;
  - Able to process fibrous and particulate slurries;
- Has no attached mechanical equipment;
  - No forced down time;
  - Low operating and maintenance cost;
- Provides hydraulic recirculation of surface layer;
  - Prevents formation of scum layers;
  - Continuously provides nutrients and inoculum for improved solids reduction.

The data collected at this scale, therefore, confirm that a SOLCON digester provides a lower cost conversion system for community-derived biomass and solid wastes compared with conventional stirred tank reactors.

ACKNOWLEDGMENT

The authors wish to acknowledge the support and assistance received from the personnel at Walt Disney Imagineering, the University of Florida, and our field scientist in the opeation of the test facility. We also gratefully acknowledge our sponsors, the Gas Research Institute and Southern California Edison.

REFERENCES

1. IGT Systems and Applications Group Communication: "Waste Resource Base," January 1987.
2. Debusk, T. A. and Reddy, K. R. (1987), *Aquatic Plants for Water Treatment and Pressure Recovery*, Reddy, K. R. and Smith, W. H. eds., Magnolia,
3. Biljetina, R., Chynoweth, D. P., Srivastava, V. J., Janulis, J. A., Razik, A., and Smallwood, S., "Biogasification of Walt Disney World Biomass Waste Blend," Final Report for Gas Research Institute, Contract 5082-223-05676, October 1986.
4. Black and Veatch, "An Economic Systems Assessment of the Concept of a Water Hyacinth Wastewater Treatment/Methane Production," Final Report for Gas Research Institute, Contract NO. 5082-511-0629, 1983.
5. Coble, C. G., Egg, R. P., and Salge, M. D. (1985), Paper presented at *Energy From Biomass and Wastes IX Symposium*, Lake Buena Vista, FL.
6. McBee, G. C., Miller, F. R., Dominy, R. E., and Monk, R. L. (1986), Paper presented at *Energy From Biomass and Wastes Conference*, Washington, DC.
7. Srivastava, V. J., Biljetina, R., Isaacson, H. R., and Hayes, T. D., *Proc. 42nd Indust. Waste Conf.*, Purdue University, Lewis Publishers, 1988.
8. Legrand, R. and Warren, C. S. (1987), *Proc. Waste and Biomass Anaerobic Digestion Workshop*, Gas Research Institute, Isaacson, H. R., ed., Chicago, IL.
9. Srivastava, V. J., Fannin, K. F., Biljetina, R., Chynoweth, D. P., and Hayes, T. D. (1987), Symposium Paper, *Aquatic Plants for Water Treatment and Resource Recovery*, Magnolia, FL.
10. Srivastava, V. J., Fannin, K. F., Chynoweth, D. P., and Frank, J. R. (1987), Paper presented at the *Ninth Symposium on Biotechnology for Fuels and Chemicals*, Boulder, CO.
11. American Public Health Association (1981), *Standard Methods for the Examination of Water and Wastewater*, 15th ed., Washington, DC.