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Large and Small Applications of Energy Farming

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LARGE AND SMALL APPLICATIONS OF ENERGY FARMING

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Abstract

The collection of solar enerby by photosynthesis and the subsequent conversion of crop matter to natural gas can be practiced in farm scale applications or very large installations. This paper discusses the design and economics of these systems.

1. INTRODUCTION

Escalating energy prices and energy shortages in recent years have become problems of national importance, resulting in a search for new feasible energy sources. This nation has an almost unlimited renewable energy source in the form of solar energy. For example, during any fourteen daylight hours, an amount of solar energy equal to our annual consumption (1975) is incident upon the surface of the United States, at an average insolation rate of 3 BTU/min-ft^2, Calvin(1) and Alich and Inman(2). Alternatively, the U.S. energy requirement could be supplied by the annual solar energy falling on an area 75 miles square (5,625 square miles). Undisputedly, solar energy is the most universal and plentiful form of energy.

1.1 SOLAR ENERGY COLLECTION

Solar radiation is an inconvenient form of energy. It is diffuse and large collection areas are required. Solar energy is intermittent and some form of energy storage mechanism must be provided. Photovoltaic and photothermal methods of conversion have respectable conversion efficiencies (5.0 to 15.0 percent) but the high cost of these systems will probably impede their widespread application.

Solar energy can also be collected by photosynthesis, a method which manufactures its own collection network and provides its own energy storage mechanism. The leaf system, or canopy, of a particular plant serves as a solar energy collecting surface. Depending on the structure of the canopy and on the type of plant, 0.2 to 4.0 percent of the total incident radiation is converted into plant matter, or biomass. Typical efficiencies range from about 1.0 percent for corn and sugarcane to about 0.2 percent for a forest.

Biomass, or chemical energy, can serve as an energy mechanism, to be harvested when needed and transported to points of usage. New technology need not be developed, since existing agricultural techniques and equipment can be utilized. Crop residues also offer an attractive source of biomass since both food and energy can be produced on the same land.

2. BIOMASS AS AN ENERGY MECHANISM

Crop matter is an inconvenient form of energy. It can be burned, but the high moisture content reduces the efficiency of combustion. Also, storage and transportation of crop matter is inconvenient and expensive. These difficulties can be overcome by converting biomass to gas. Pyrolysis and hydrogasification are two processes for gasifying organic matter. These processes operate at elevated temperatures and pressures, and although still under development, suffer from low conversion efficiencies, 30 to 50 percent, Anderson[3] and Feldman[4].

Plant matter can also be converted to methane biologically by the process of anaerobic digestion. This process occurs at ordinary temperatures and pressures with a theoretical thermal conversion efficiency as high as 94 percent, Hungate[5]. Anaerobic digestion is a three stage process. Solid organic material is enzymatically dissolved. Soluble organics are then metabolized by bacteria to organic acids and alcohols. Methane bacteria convert these fatty acids and alcohols to methane and carbon dioxide.

Anaerobic digestion has been studied extensively as a municipal waste treatment process; however, little data is available concerning the anaerobic digestion of crop matter in continuous culture. Hay, cornstalks, comfrey, municipal refuse, and oak leaves have been studied in the University of Missouri-Rolla laboratories to determine the feasibility of producing methane from various materials. These studies indicate that up to 19.5 ft^3 of methane is produced per pound of carbon destroyed. Typical carbon content of these materials is 30.0 to 40.0 percent; and, with 80.0 percent carbon destruction, up to 6.0 ft^3 of methane are produced for each pound of dry crop matter.

3. APPLICATIONS OF BIOCONVERSION

Bioconversion could be used on a large scale with energy crops or crop residues produced on farms and transported to a central location for conversion to methane. Each farmer could also devote a few acres to the production of an energy crop, or use crop residue, to provide the energy for his own farm. Design data for these systems are scarce. This paper presents the design and economics for both a crop digester system to supply the electricity and gas requirements of small farms and for a very large installation to produce 50 $\overline{M}$ SCFD methane.

3.1 FARM BIOCONVERSION SYSTEM

Energy is consumed in many forms on the modern farm. Gas, usually liquified petroleum gas (LPG), and electricity are two forms of purchased energy that can be replaced by a crop digester. Figure 1 is a diagram of a crop digester system, showing the equipment needed to produce gas and electricity. Ground crop matter is fed to a reactor where a mixture of about 65 percent methane with 45 percent carbon dioxide is produced. This gas is stored or burned for cooking or heating. This low BTU gas can be substituted for LPG for most home uses with only an orifice adjustment. Electricity for lighting or appliances is produced with a small generator driven by a gas fired engine.

The basic design in this study considers the energy needs of the farmhouse only. Fuel for trucks and tractors could be provided with compressed methane. However, substitution of methane for gasoline was considered too expensive and hazardous to include at this time.

The LPG requirement for heating the average home is estimated to be 1220 gallons per year, Dawson[6]. An additional 280 gallons per year was assumed for cooking and water heating. Electric power usage was set at 900 kwh per month, Fed. Power Com.[7]. Table I lists the energy consumption data for the farm, and the equivalent methane requirements. An average gas consumption of 730 SCFD of methane is required, with a maximum consumption of 980 SCFD required from October through March because of the increased heating load.

Digester Kinetics: A digester can be operated either as a batch reactor or as a pseudo-continuous flow reactor, in which feed additions and effluent withdrawals are made each day. A batch system was chosen for the farm application, since it requires much less attention and there is less opportunity for exposure to oxygen. Data from Fry[8], Klein[9] and Singh[10], as well as lab studies in the UMR labs, indicate that 80 percent destruction of the carbon loaded into batch digesters can be converted to methane and carbon dioxide in 60 days.

The primary disadvantage of a batch digester is that its output is not constant. This problem can be solved by using several reactors in parallel, operating on staggered schedules, so that at least one digester is always near the peak of its output. To minimize fluctuations in gas production, six parallel digesters were designed for the farm installation, with one to be loaded every ten days.

Six reactors, each with a volume of 1614 gallons, would produce an average of 730 CFD methane. A reactor size of 2300 gallons was chosen to provide for the maximum production rate and allow excess volume for gas space and scum formation on the reactor slurry. Carbon steel tanks were used.

Acreage Requirements: Biomass requirements are 24.4 tons of dry crop matter per year to supply 730 SCFD. If conventional hay is the energy crop, 5-10 acres would be needed to provide the energy needs of the farmhouse. If crop residues are used, acreage requirements diminish in importance since food crops are being grown on the same land. About eight acres of corn would supply enough corn stalks to operate the digester.

Temperature Control of the Digesters: For optimum operation with mesophilic bacteria, the digester temperature must be maintained at 95°F, which requires heating most of the year. Heat could be supplied from the methane produced. The engine generator to produce electricity is about 25 percent efficient. Sixty percent (10, 100 BTU/hr) of the energy in the combustion gases is available as waste heat in the exhaust gases or as radiation from the engine. Therefore, the reactor heating system should be designed to make use of this waste heat.

Several methods of maintaining digester temperature with the waste heat from the generator were considered. Water, heated by the engine exhaust, could be pumped through heating coils in the insulated digester tanks. Hot gases (methane and carbon dioxide) could be blown into the bottom of the digesters to provide mixing as well as heating.

A third method involves placing the uninsulated tanks and generator in an insulated building. The amount of waste heat recovered is increased since the heat from the engine cooling fins is also available. A building, 31 x 18 x 8 ft. would be adequate to house the equipment. Six inches of fiberglass insulation on the walls and ceiling, and three inches of loose sawdust on a dirt floor reduce the heat losses so that the available waste heat is adequate to maintain 95°F inside the building with a 20°F outside temperature. The room temperature is controlled with air circulation through a space heater using the exhaust gases as heat. The cost of materials for this system was estimated to be $1360. The heated building design was chosen as the temperature control system for the farm installation on the basis of cost and simplicity.

Other Equipment: Gas storage is required to accommodate small variations in demand. Gas compression is impractical and commercial floating head tanks are too large and expensive to be used. Therefore, a liquid displacement storage facility was designed. A steel tank, open at one end, inverted in a brine-filled pit, provides a constant pressure, variable volume gas storage tank. A 400 cu. ft. tank is sufficient to account for oscillations in digester output. Larger fluctuations, such as seasonal variations must be accounted for by varying the size of the reactor charges. Pressure inside an 8 ft. dia., 8 ft. long, 10 ga. steel tank would be 5 inches of water, which is adequate to overcome friction losses and operate burners. The gas pressure can be increased by adding weight to the top of the tank.

The generator to supply electric power for the farm must be sized for an average of 900 kwh/mo. or 1.2 kw. However, maximum load could be as high as 4 kw with simultaneous operation of several appliances. Since the fuel gas is 35 percent carbon dioxide, the generator engine must be derated about 30 percent. Therefore a 6 kw, 120 VAC, 60 Hertz generator-engine system was included for the digester system. A battery and AC inverter are used to smooth out starting and stopping the generator with electrical demand.

Agitation of the digesters is necessary to promote better digestion. Continuous agitation is desirable, but the equipment required would be expensive. Periodic agitation, on the other hand, has been found to produce satisfactory results, and can be accomplished with cheap, hand-driven mechanisms.

A forage chopper is necessary to reduce the size of the crop matter before feeding to the reactors. A sludge pump with a capacity of about 500 gallons per hour is needed for emptying the digesters. Finally, a tank must be provided to store part of the reactor effluent for use as seed bacteria for the subsequent reactor charge. A 200 gallon tank, or about 10 percent of the reactor volume, is provided for this purpose. Other incidental equipment includes gas piping, valves, loading hatches on the tanks, lighting for the building, and wiring.

Economics of the Farm Energy System: Table II shows the estimated capital costs for two sizes of farm digestion systems. The minimum size plant produces an average of 730 SCFD for the small farmhouse only. A plant of twice this size is also included. The total estimated investment for new equipment is $7870 for the minimum size system shown in Figure 1. As noted, about half the cost is for reactors and the building.

Operating costs for the farm energy system include raw materials (energy crop) and maintenance. Operating labor was assumed negligible. Most of the labor involved is in growing and harvesting the energy crop, and this cost is included with the price of the raw materials.

Maintenance was assumed to be 2 percent of investment, or $157 per year for the smallest installation. The cost of the raw materials depends on the type crop used. Corn residue can be collected for $4.73 per 1600 pound bale, or $143 per year, Successful Farming[11].

Table III shows the return on investment and payout for the farm digester installations based on an energy cost of $5/$\overline{M}$ BTU for LPG and electricity. Net savings, after expenses, are $844 per year for the small system and $1788 per year for the large plant. The return to the farmer ranges from 10 to 17 percent per year.

Rising energy costs will certainly improve the profitability of the digestion system.

A further improvement in the economics can be achieved by reducing the investment. For example, if a farmer already owns a forage chopper, the capital cost for the system is reduced by $1000. An unused outbuilding or a portion of a barn could be converted to enclose the digesters with resultant savings in investment. Buying used equipment instead of all new materials could further reduce the investment. The energy system under installation on a farm at Drury, MO is expected to cost $7,000.

3.2 LARGE BIOCONVERSION SYSTEM

Figure 2 shows the necessary processing steps and equipment for the production of 50.0 million ft^3 of methane per day. Approximately 4460.0 tons of biomass are required per day. Plant matter is field cut, baled into large one ton bales and transported to a stockpile at the central plant. Crop residues may be stored in the field and harvested at the farmer's convenience.

The biomass is passed through a shredder before entering the reactors. Storage silos provide one day of feed retention. Ground biomass is mixed with water to a concentration of 10 percent solids before entering the reactors. The reactors are five million gallon floating head steel insulated tanks and are operated in series. Heating and agitation are provided by gas recirculation.

The product gas stream is compressed to 15 psig. Carbon dioxide and hydrogen sulfide are scrubbed from the methane with monoethanolamine solution. A glycol scrubber dries the gas to produce pipeline quality methane.

By utilizing waste heat from the compressor exhaust and heat exchange between the process streams, only 7.5 percentof the methane produced is required for compression and heat within the process. The energy requirement for collecting and transporting crop materials to the plant site (an average distance of fifty miles), including the energy requirement of the collection equipment itself, is equivalent to three percent of the product methane, Alich and Inman[2], Berry and Fels[12], and Pimental[13]. Therefore, the net efficiency of the biological conversion process is about 89.5 percent.

Process Economics: Table IV presents the economics for the process utilizing crop residues. The total capital investment is $75.47 million, including a 30.0 percent contingency. Over 65.0 percent of the investment is for the reactors. The results are designed using a first order constant of .086 days^{-1}, as measured in the UMR laboratories. All equipment costs are based on data by Guthrie[14].

An extensive study has concluded that biomass can be produced and harvested for $10.00 per ton, Alich and Inman[2]. Using this value, total raw material cost is $14.63 million.

Labor was calculated as 0.86 percent of the investment. Maintenance and depreciation were calculated as 5.0 percent of the investment and taxes and insurance as 2.0 percent. Total operating costs are $24.91 million. With revenue at $33.85 million ($2/MSCF), net profit is $6.08 million per year and the return on investment is 17.08 percent.

The liquid effluent from the reactors will contain the undigested carbon and all the minerals from the original crop matter. This material should be an excellent soil amendment; however, its fertilizer value is not included in these economic projections.

Since reactor costs constitute a large percentage of the total capital investment, the process economics are strongly dependent upon the reaction rate and, therefore, upon the specific rate constant. Clearly, additional study of this process should concentrate on the reaction kinetics.

Since the anaerobic process has not been studied from the standpoint of optimizing yields, it is reasonable to expect that significant improvements in the rate constant can be expected with increased study. Separating the reaction steps would allow operating each stage at its particular optimal conditions of temperature and pH. Using improved microbial strains at each stage could enhance the hydrolysis of the solid biomass and increase the conversion of the soluble organics to organic acids. Concentrations of intermediate organic acids could be controlled at a significantly higher level, thereby increasing the rate of the methane producing step. Separation and return of microorganisms to each stage should also enhance the reaction rate.

4. SUMMARY AND CONCLUSIONS

Bioconversion can be applied on either a small or a large scale. This energy alternative is attractive at today's fossil energy prices. Further study should lead to even more attractive economics. The feasibility of these systems needs to be proven in practical applications.

5. REFERENCES

1. Calvin, M., "Solar Energy by Photosynthesis," Science 184, 375-381 (1974).
2. Alich, J. A., and Inman, R. E., "Effective Utilization of Solar Energy to Produce Clean Fuel," Prepared for National Science Foundation, RANN, Final Report (1974).
3. Anderson, L. L., "Energy Potential From Organic Wastes: A Review of the Quantities and Sources," U.S. Dept. of the Interior, Bureau of Mines Information Circular 8549, Washington, D.C. (1972).
4. Feldman, H. F., "Pipeline Gas From Solid Wastes," Chem. Eng. Prog. 67, No. 12, (1972).
5. Hungate, R. E., "Potentials and Limitations of Microbial Methanogenesis," ASM News 40, No. 11, (1974).
6. Dawson, D. O., "TERA and Househeating Costs", American Gas Association Monthly, 57.6 (June, 1975).
7. __________, Statistics of Privately Owned Electric Utilities in the United States, Fed. Power Com. (1972).
8. Fry, L. John, Practical Building of Methane Power Plants, Standard Printing, Santa Barbara, CA. P. 37 (1974).
9. Klein, S. A., "Anaerobic Digestion of Solid Wastes", Compost Science, 13.1, (Jan/Feb, 1972).
10. Singh, Ram Bus, "The Bio-Gas Plant-Generating Methane From Organic Wastes", Compost Science, 13.1 (Jan/Feb, 1972).
11. __________, "Second Harvest", Successful Farming, (Sep, 1974).
12. Berry, R. S., and Fels, M. F., "The Production and Consumption of Automobiles," Dept. of Chemistry, Univ. of Chicago, Chicago, Ill., 56 (1973).
13. Pimental, D., World Food, Energy, Man and Environment, Ann Arbor Science, Mich., 1975, pp. 5-16.
14. Guthrie, K. M., "Data and Techniques for Preliminary Capital Cost Estimating," Chemical Engineering, 76.6 (March 24, 1969).

TABLE I. ENERGY REQUIREMENTS FOR A TYPICAL FARM

ITEM	DEMAND	
	Average	Maximum
LP Gas - (gal/mo.)	125	213
Methane Equivalent-SCFD	350	600
Electricity - (kwh/mo.)	900	900
Methane Equivalent*-SCFD	380	380
Total Methane Demand	730 SCFD	980 SCFD

*with 25 percent generation efficiency

TABLE II. CAPITAL COSTS FOR FARM DIGESTER SYSTEMS

AVERAGE SIZE, SCFD	CAPITAL COST, $	
	730	1460
6 steel tanks	2460	4080
6 kw generator, 120 VAC, 60 Hz, with engine	1250	1250
Gas storage tank with concrete pit	700	900
Forage chopper with blower	1000	1000
Building materials	1060	1575
Heater	300	400
Sludge pump, 10 gpm	200	200
Piping, agitators, valves, misc.	400	600
Labor	500	700
Totals	$7870	$10705

TABLE III. PROFITABILITY OF FARM CROP DIGESTION BASED UPON ENERGY AT $5.00/$\overline{M}$ BTU

SIZE, SCFD	730	1460
Capital Cost, $	7870	10705
Savings, $/yr	1144	2288
Operating Cost, $/yr		
Energy Crop	143	286
Maintenance	157	214
Total Cost	300	500
Profit, $/yr	844	1788
Return on Investment, %	10.7	16.7
Payout, years	9.3	6.0

TABLE IV. ECONOMIC ANALYSIS OF METHANE PRODUCTION FROM FUEL CROPS

	Cost
Capital Investment (in $\$\overline{M}$)	
Digesters	$32.39
Grinding and Storage	1.17
Compressors	1.90
Pumping and Piping	2.00
Strippers and Absorbers	0.31
Heat Exchangers	0.96
Contingency (30%)	11.62
Total	$50.35 $\overline{M}$
Revenue ($2/MSCF)	$33.85 $\overline{M}$/yr
Operating Costs (in $\$\overline{M}$/yr)	
Raw Material ($10/ton)	$14.63
Power	0.26
Water	0.32
Labor	0.43
Maintenance	2.52
Depreciation	2.52
Taxes and Insurance	1.01
Total	$21.69 $\overline{M}$/yr
Gross Profit	$12.17 $\overline{M}$/yr
Net Profit	$ 6.08 $\overline{M}$/yr
Return on Investment	17.08%

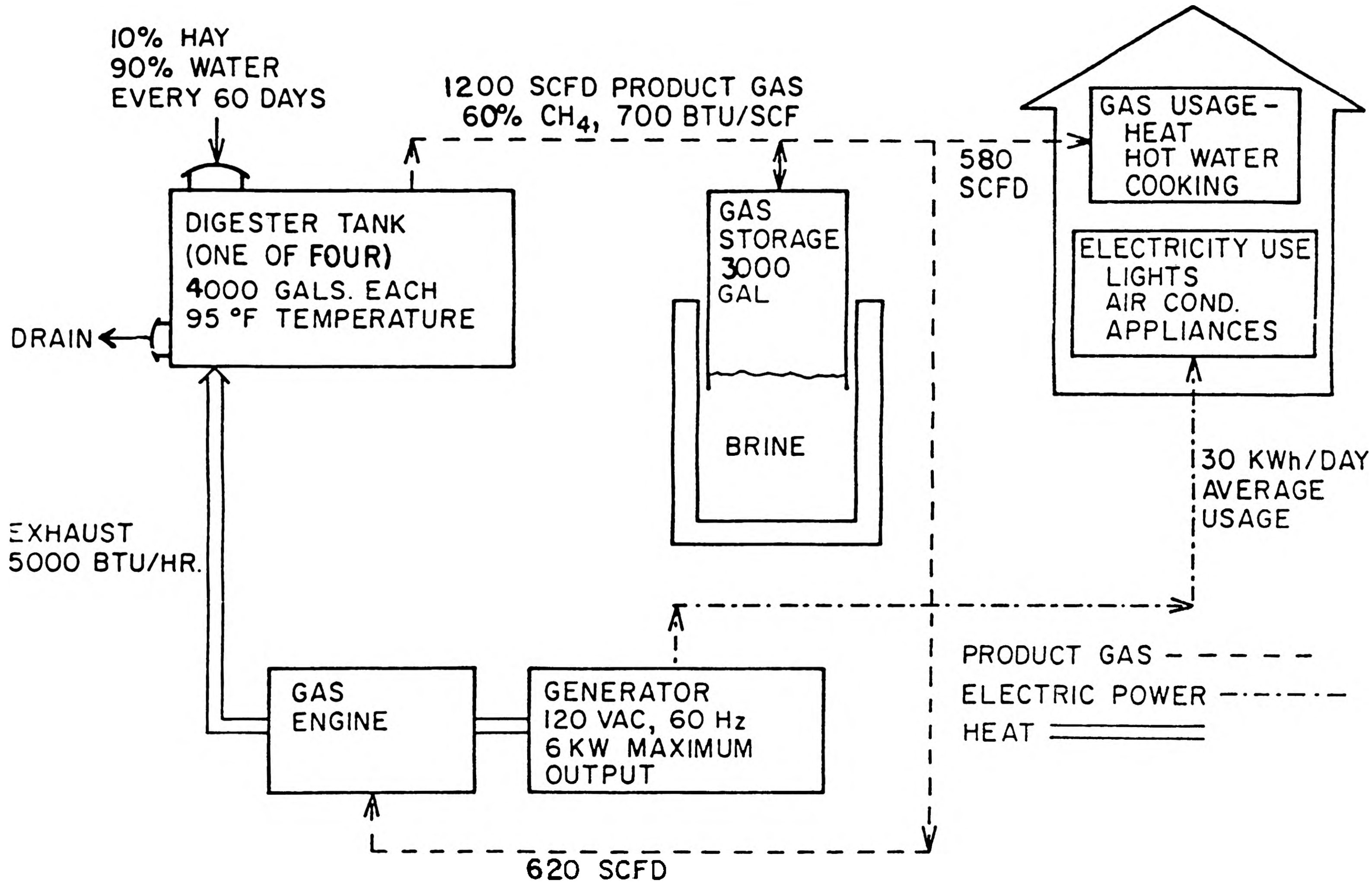

FIGURE I. SCHEMATIC OF CROP DIGESTER SYSTEM

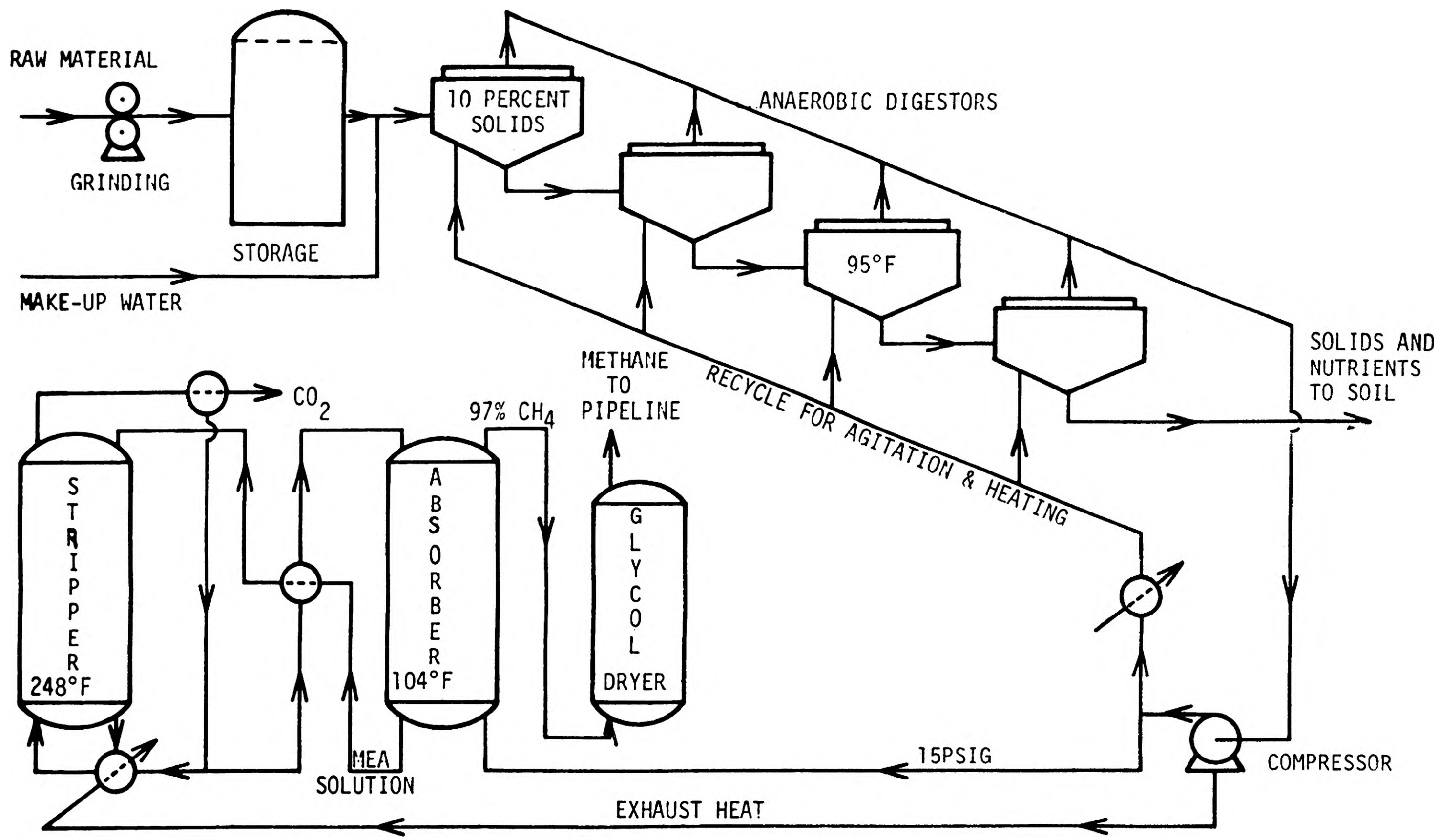

FIGURE 2. BIOCONVERSION PROCESS FOR PRODUCING METHANE