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OPERATION AND EVALUATION OF A 50,000 GALLON ANAEROBIC DIGESTER AT THE STATE HONOR FARM DAIRY, MONROE, WASHINGTON

Final Report, 1977–1978

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MASTER

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Operation and Evaluation of a 50,000 Gallon Anaerobic Digester at the State Honor Farm, Monroe, Washington

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Preface

The Monroe digesters were operated over the last nine months by Skip Brink and Pat Moodie. Without their assistance and attention to detail, this report and much of the observation and research lines would have been overlooked. In addition to the research and operation of the facility, the tremendous job of clean-up and repair necessary at the outset of the program made the rest of the work possible.

Randy Skoog, Evan Brown and the Summer Youth Employment Program in Snohomish County assisted in the clean-up process.

We would also like to acknowledge the volunteers and the prisoners who assisted in sandbagging through the night to protect the plant from flood water in early December. Lastly, we need to acknowledge the State Honor Farm and State administrators who never made our lives easier, but allowed us to work with few interruptions and, of course, provided us with such a wonderful substrate.

The support of the Department of Energy, Fuels from Biomass Coordinating Group was invaluable to us in pursing this research. Their suggestions provided Ecotope insights which we might otherwise have ignored. In this sense, the quality of this work was greatly enhanced by their existance. In particular, the support of Bill Jewell of Cornell and Don Wise of Dynatech R/D were invaluable throughout the year's work. The support of Dr. Roscoe Ward and Dr. Robert Spicher and the Fuels from Biomass program people were also important.

The preparation of this report was a team effort. The authors would like to thank Liz Stewart for the editing and typing, Carol Oberton for graphics support, and Evan Brown for consulting and review of the system operation.

The products mentioned in this report were chosen during the design phases of the project and effort to document their performance should in no way be construed as a product recommendation. Ecotope Group accepts full responsibility for the contents of this report.

Portions of this report appeared in the First, Second and Third Quarter Operating Reports and "Operation of an Anerobic Digester at the Washington State Dairy Farm," by Ken Smith, a paper submitted to the Institute of Gas Technology 1978 Fuels from Biomass conference.

Ecotope Group
1 July 1978

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1.0 INTRODUCTION AND PROJECT SUMMARY

Ecotope Group has been under contract to the United States Department of Energy to operate a full scale anaerobic digester facility for dairy cow manure at the State Reformatory Honor Farm near Monroe, Washington. The system was designed by Parametrix Engineering and Ecotope Group under contract with the Washington State Department of Social and Health Services (DSHS) and the State Department of Ecology (ECOLOGY).

1.1 System Design

The system as designed and operated is a complete-mix mesophilic digester consisting of two 189 m^3 (50,000 gallon) glass-enameled, steel tank reactors (Figure 1.1). Operating temperature is 35°C (95°F). Mixing is high rate by gas recirculation. This systems represents a "state-of-the-art" technology transfer from typical municipal sewage treatment applications. As such, it was designed to have numerous components common to sewage treatment plants such as:

(1) Rigid tank digesters
(2) Continuous mixing
(3) Name-brand gas safety equipment
(4) Single-use pumps.

An emphasis was placed on the use of "off-the-shelf" components which are easily obtainable. It was felt that employing equipment which has already been proven and accepted in the agricultural sector would accelerate the duplication and wide-spread utilization of digestion technology.

A heavy design emphasis was placed on energy conservation. The tanks were well-insulated (R>20 throughout) and an influent/effluent heat exchanger was designed and installed to reduce the most significant heat demand of the system. A two-tank system was employed to allow maximum flexibility in adjusting the loading rate and retention time to optimize the performance of the system.

A laboratory was established to monitor the basic biological parameters of the system and to monitor its response to changes in loading, mixing and heating. Gas and electric meters were installed to monitor the energy production and consumption of the system. This data was used to provide a detailed energy and economic analysis of the system which can be used to evaluate the economic feasibility of similar systems.

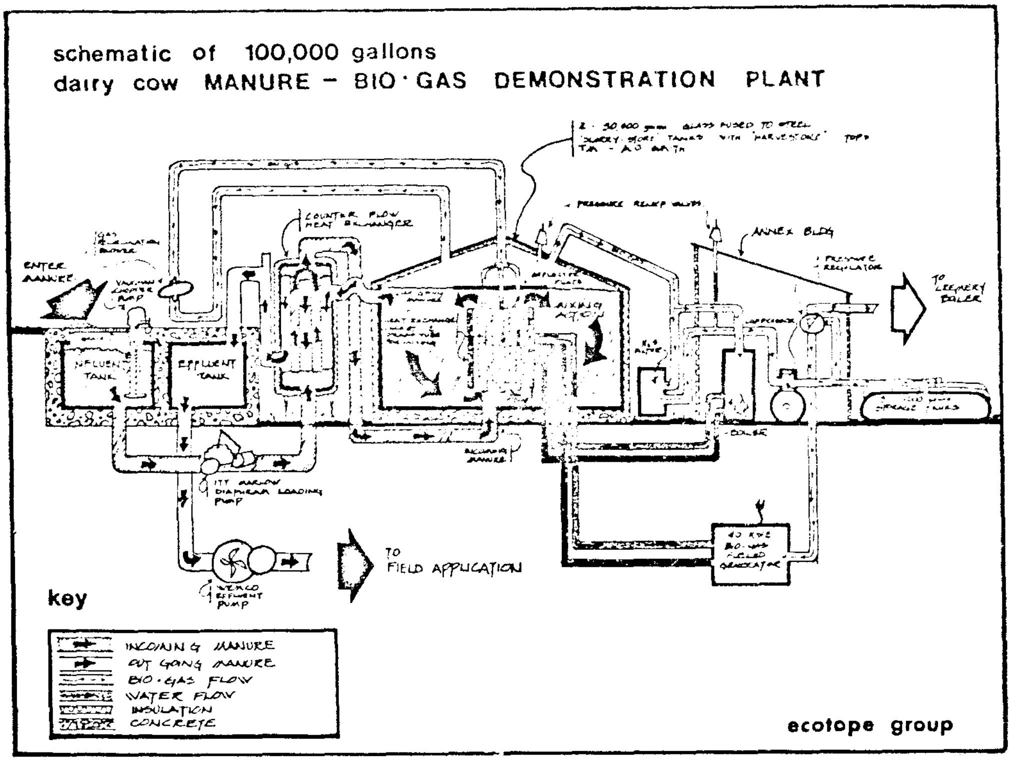


Figure 1.1

1.2 Project Objectives

The objectives of the project were:

1.2.1 To bring the system to an efficient operating condition.

1.2.2 To test out and evaluate the performance of various system components.

1.2.3 To demonstrate the use of an influent/effluent heat exchanger.

1.2.4 To monitor the biological health of the system.

1.2.5 To maximize the net energy of the system.

1.2.6 To perform an economic analysis of the system.

1.2.7 To publish an operator's manual with a step-by-step description of system operation.

1.3 Current Operation

The plant was started in August 1977 and has been operated continuously since that time. Currently, only one reactor tank is in use, producing 200 to 260 m^3 (7500-9000 ft^3) of bio-gas per day at an average of 61% methane gas. The heat value of this production is about 5.3 GigaJoules (5mmBTU) per day. Currently, this represents a limit to this system since the digester is processing all of the available manure resources.

Operator time has been reduced to one to two hours per day. This time is spent in mixing manure, loading the digester and checking the system operation. Additional time is spent doing lab work, reading gas and electric meters and analyzing data. However, this work would not be necessary in a standard farm application.

The biological performance of the Monroe digester has been remarkably stable. Even under erratic conditions -- freezing, flooding, and great temperature and loading fluctuations -- there has been no noticeable stress shown by the biological system.

1.4 Design Versus Operational Experience

This program has demonstrated the viability of anaerobic digestion for the production of fuel gas in a dairy farm operation. While design flaws in the system (largely based on municipal sewage treatment technology) prevented a demonstration of the total working system, adequate inferences can be made to establish preliminary design specifications and costs for similar systems on operating dairy farms.

A good deal more experience with these systems is required to insure high quality systems engineering. The microbiology of these processes is well understood. The experience at Monroe has underscored the great gap between the laboratory findings and the practical and commercial applications of these findings in anaerobic digestion.

Since the digester at Monroe was not built as an experimental facility but as part of an operating dairy farm, the decision was made to avoid systems developed for Third World use because of their labor intensive nature and less-than-optimal production and because of problems associated scum formation. At the time of design, there were no working systems tailored to the dairy farm situation. Consequently, standard sewage treatment model was used and sanitary engineers were employed to design the system. However, the nature of the two differing substrates and the contexts in which the digesters operate make direct sewage treatment technology transfer inappropriate for dairy farm operations.

One of the most obvious differences between anaerobic digestion on a dairy farm versus a municipal sewage treatment system is the lack of public subsidies. In a municipal plant, the public is paying for digestive services. In a dairy farm application, disposing of manure is solely the problem of the farmer and the cost of the solution must be borne by this individual. The long term economics of these systems as energy producers are thoroughly dominated by the initial capital costs. Since dairy farming operation does not have a high margin of profit, it is important that a system's engineering be optimized to reduce unnecessary capital costs.

1.4.1 Sizing Tanks. Accurate sizing of the reactor vessel to avoid paying for unneeded volume is necessary. Digestion tanks should be sized for high loading rates and retention times as short as ten days. With long retention times, percent reduction of volatile solids increases, but the units of gas per unit of destroyed solids decreases. The tradeoffs between increasing destruction and optimizing gas production should be considered for specific given applications.

1.4.2 Pumps. Every attempt should be made to minimize the number of pumps used in the system. Utilizing gravity flow for loading or unloading the system can eliminate one pump. Other pumps can be used for multiple purposes. A pump which is used to mix the influent could also be used to transfer manure to a holding lagoon or to pump the effluent out onto the field. This necessitates the use of flexible plumbing as opposed to the hard plumbing of municipal sewage treatment plants with their single-use pumps. The use of flexible hose plumbing not only facilitates the multiple use of pumps, it also reduces the pumping head loss associated with elbows and tees.

There is a need for good engineering data to establish pumping specifications. Pumps must be able to handle high solids and high loading rates.

In addition, characteristics of the substrate (such as bedding) must be taken into account for choosing pumps which can handle the substrate. More field experience is necessary to determine what equipment best meets the needs of a given loading regime and of a given substrate.

1.4.3 Mixing. It is becoming increasingly apparent that the need for mixing in an anaerobic system has been overestimated. Work done at Cornell (Jewell, 1977) and the University of Wisconsin (Abeles,*et al*,1978) have demonstrated that mixing is unnecessary in a plug flow system. Experience at Monroe indicates that the percent total solids loaded is the determining factor in maintaining a complete mix system. When % total solids in the digester were less than 8%, solids stratification was apparent, even with constant mixing. When the loading rate was increased to 10% solids and the solids content of the digester rose above 8%, stratification decreased -- even when mixing was reduced to only ten minutes each hour. Even this amount may prove to be greater than necessary.

Anaerobic digestion systems should be designed to load at as high % solids as possible, and mixing equipment should be multiple use since it is not often needed. Mechanical mixers could be used for mixing influent and for mixing digester tank contents. Both could be run by a power take-off from a tractor, thereby eliminating the need for motors which are used only a short time each day.

1.4.4 Heat Exchange. Being able to recover the heat from warm effluent to preheat the influent is an attractive option from energetic, biological and economic standpoints. An influent/effluent heat exchanger operating at 40% efficiency will reduce the heating energy needs of a system by 35% and will thereby substantially improve the economics. It will also lessen the temperature fluctuations in the tank during influent loading. One of the problems associated with influent/effluent heat exchange is that to be most effective, it requires continuous feeding which means constant pumping and may increase operating problems (clogging, breakdown, etc.).

Electricity was produced at the Monroe site daily in December and January using a Waukesha engine with a Kato generator. It was operated at less than full load and achieved only 11% efficiency. However, its coolant water was circulated through a draft tube-heat exchanger. The waste heat produced was more than was needed to heat the digester during the winter months. This improved the overall efficiency of this operation.

1.4.5 Gas Safety Equipment. Name-brand gas safety equipment designed for municipal sewage treatment plants was used, adding 5% to the costs of building the system. Lower cost gas safety equipment must be developed for use within the context of a farm operation.

1.5 Economics

In economic terms, the Monroe digester as presently operated appears to represent a lower limit of economic feasibility, except when compared to marginal (1985) oil and gas costs.

The rate of return on invested capital for these systems is not favorable. If the rate of the alternative investment is 5%, 200-cow dairies are at the lower limit. If the gas produced is used to generate electricity, when compared to the cheap hydro power of the Pacific Northwest the rate of return is too low to be considered a good investment, even for large systems. This anomaly suggests the need for direct subsidies or credits before electricity could be generated this way. If the gas is to be used to generate electricity, the technology should be applied in regions where power is more expensive. Farms with a use for the gas directly on-site are at an obvious economic advantage.

The complete mix mesophilic system can be adapted to dairy farming operations to be cost competitive with conventional energy. There is a substantial economy of scale issue which suggests that this technology should be applied to larger dairies (over 200 cows). In this sense, the design conditions for the Monroe facility approach the lower limits of economic feasibility for dairy farm applications. It is clear that better designs can be developed from this digester and that competitive systems can be installed.

2.0 SYSTEM OVERVIEW

2.1 Farm Description

The State Dairy Farm is about 56 km (35 miles) northeast of Seattle (Figure 1.1). It is a minimum security penal institution with thirty residents and ten cadre who operate a creamery to process milk, cheese and ice cream. This 250-acre farm has 400 head of Holstein cattle, with a milking herd of about 200.

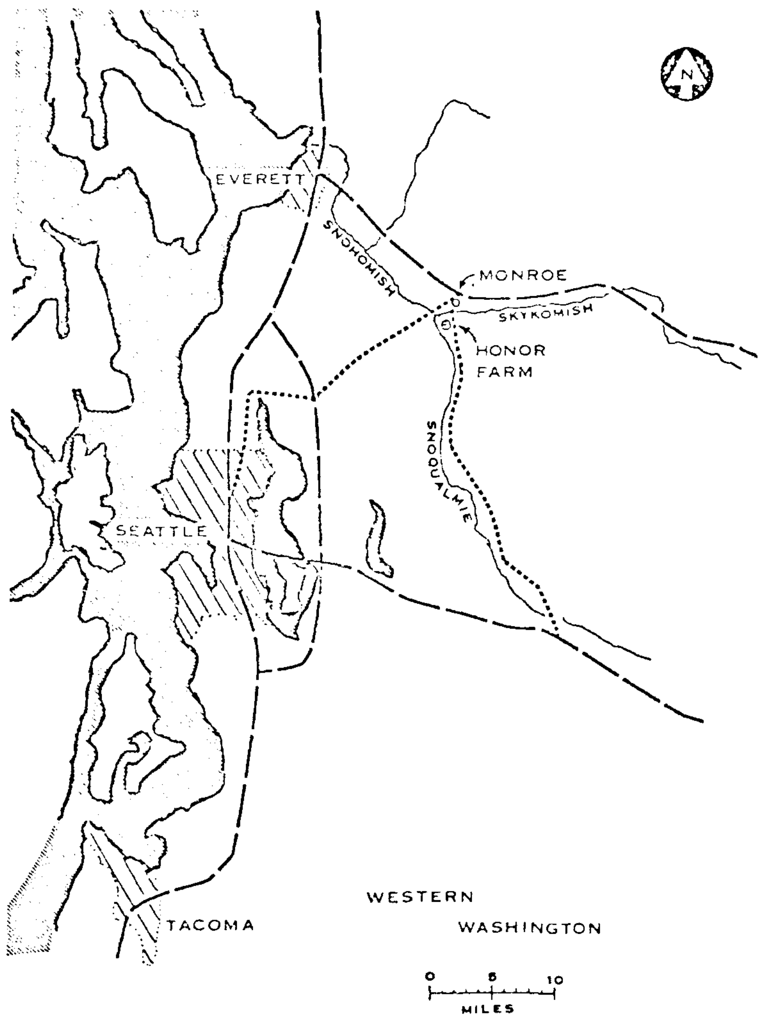


Figure 2.1
Project Location Map

The milking animals are housed in a covered loafing shed. The loafing shed consists of individual sawdust-bedded stalls and a concrete floor where manure and urine are removed by a rear-mounted scraper on a diesel tractor aided by water flushing. Sumps in the barn are connected by pumps to an earthern storage lagoon. Sprinkler gun-type irrigation is used for field application of manure (Figure 1.2).

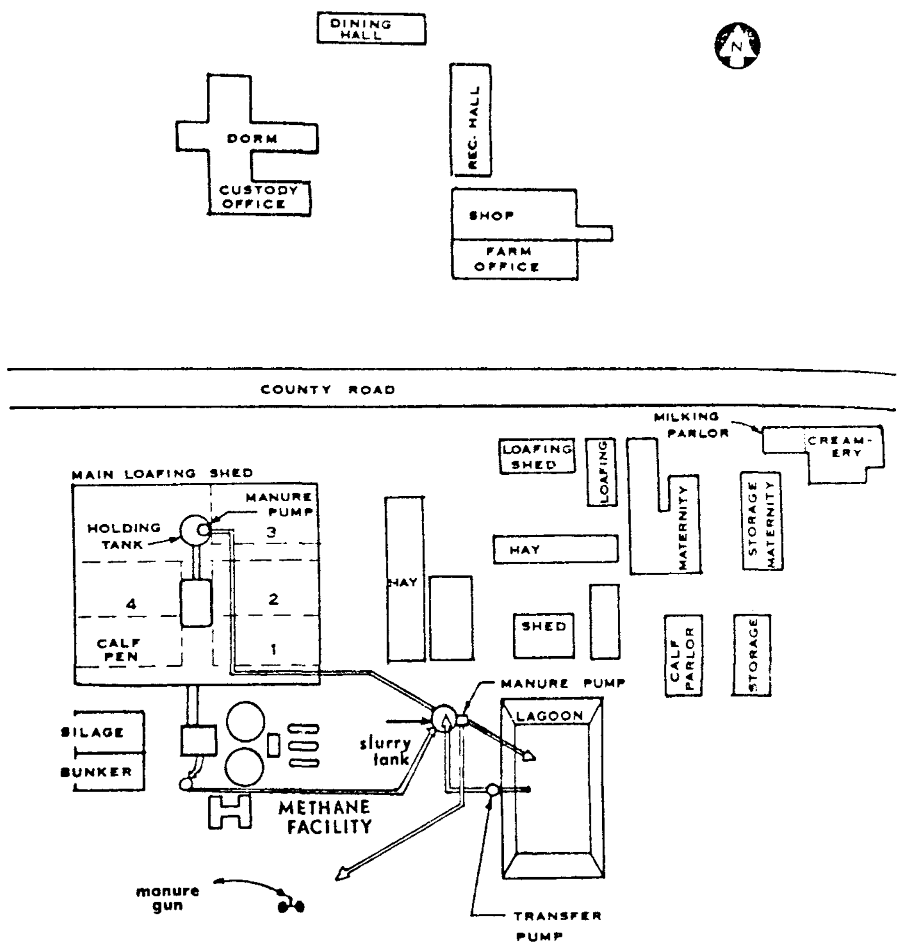


Figure 2.2

Monroe State Dairy Farm
Plot Plan

2.2 System Description

2.2.1 Digester Tanks. In order to achieve maximum output at minimum cost, "off-the-shelf" manure storage tanks were chosen (Figure 2.3). The digester tanks are manure storage tanks manufactured by A.O. Smith Harvestore Corporation -- with a standard silo roof which is air tight and capable of holding pressure to 508N/m^2(20"WC). The entire system was installed with a trained crew supervised by a local Harvestore dealer. Construction time was about one week per tank.

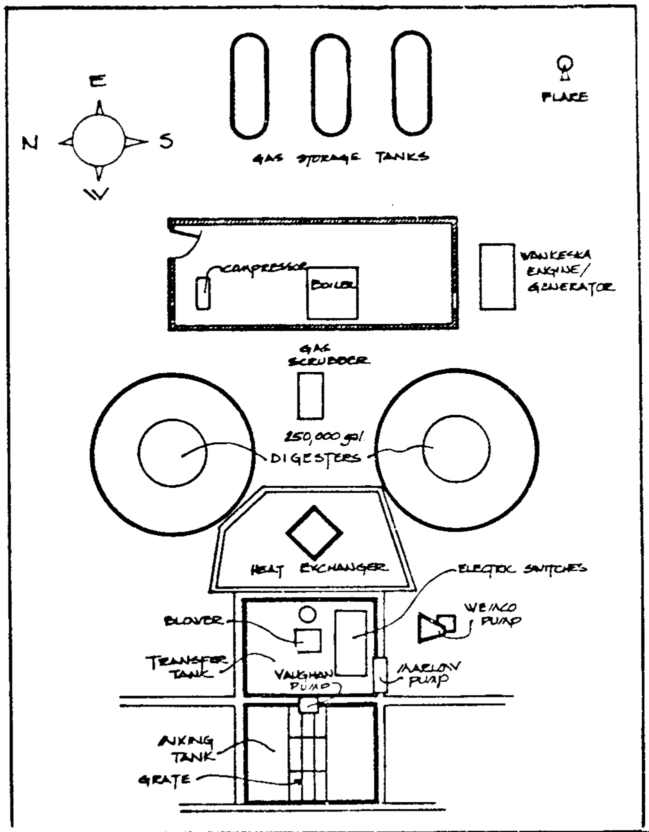


Figure 2.3
Monroe Digester Site Plan

2.2.2 Tank Insulation. In order to reduce tank heat losses and increase net gas production, insulation was applied to all exposed tank surfaces. The exterior of the tank walls were covered with four inches of Dow Styrofoam SM_{tm} (R-22), protected by a shield of corrugated galvanized iron roofing sheets. The interior of the roof was sprayed with 3½" of polyurethane foam (R-21).

2.2.3 External Heat Exchanger. The heating required to bring the influent to 35°C (95°F) is about four times that of the heat lost through the walls and roof of the tank. Therefore, an external counter-flow heat exchanger was designed and built by Howard S. Reichmuth. This heat exchanger was designed to recover 58% of the heat from the effluent and transfer that heat to the incoming stream of fresh manure. Greater than 50% heat exchanger was possible using a shell and tube counter-flow design (Reichmuth, 1977). To date this system has not functioned and further design modifications appear necessary.

2.2.4 Loading. The plant is loaded with manure scraped daily from a 180-cow milking herd housed in an environmental loading shed immediately adjacent to the site. It is diluted and mixed by a Vaughan chopper pump in a concrete tank. The manure is diluated with water to 10% solids to facilitate pumping and handling. The plant was designed to handle 9% solids on the assumption that any greater solids would present significant mixing problems. As a result, 10% solids is a practical limit of the pumping equipment although the mixing and heating systems could handle much more.

The manure slurry is then loaded by the Vaughan pump directly into the reactor tanks (Figure 2.4). The heat exchanger is by-passed because the pump required for continuous loading necessary to the heat exchanger is not

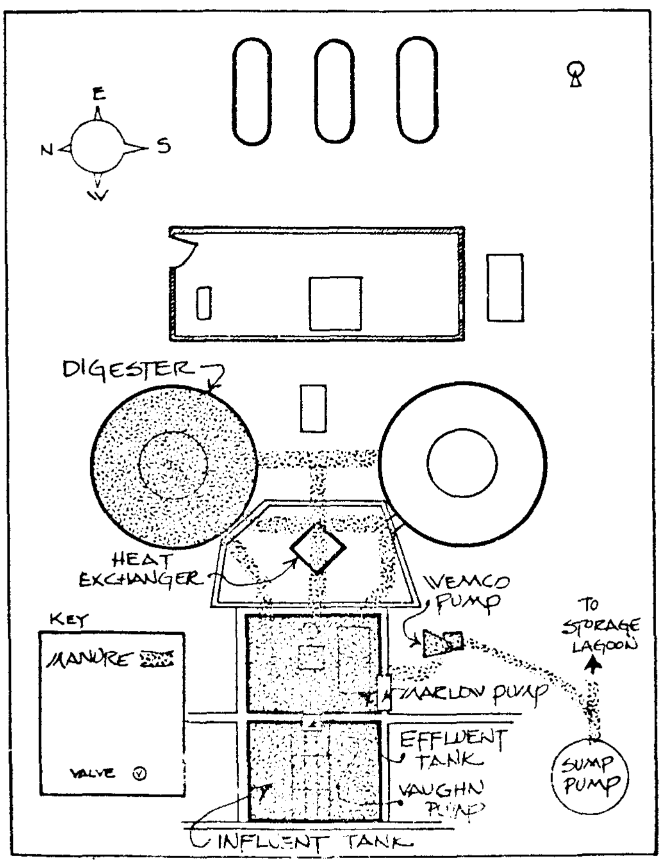


Figure 2.4
Manure Loading System

operational. The tanks operate on an overflow system. As the influent enters the tank at the bottom, the top layer is displaced through an overflow pipe and drains into a holding tank. From there it is transferred to the Farm's manure handling system.

2.2.5 Mixing System. Gas recirculation mixing was chosen for its ease of installation and for its integration with the internal heating system (Figure 2.5). A draft tube is employed to aide in dispersing the slurry. The draft tube is also a heat exchanger, having concentric walls which form a water jacket.

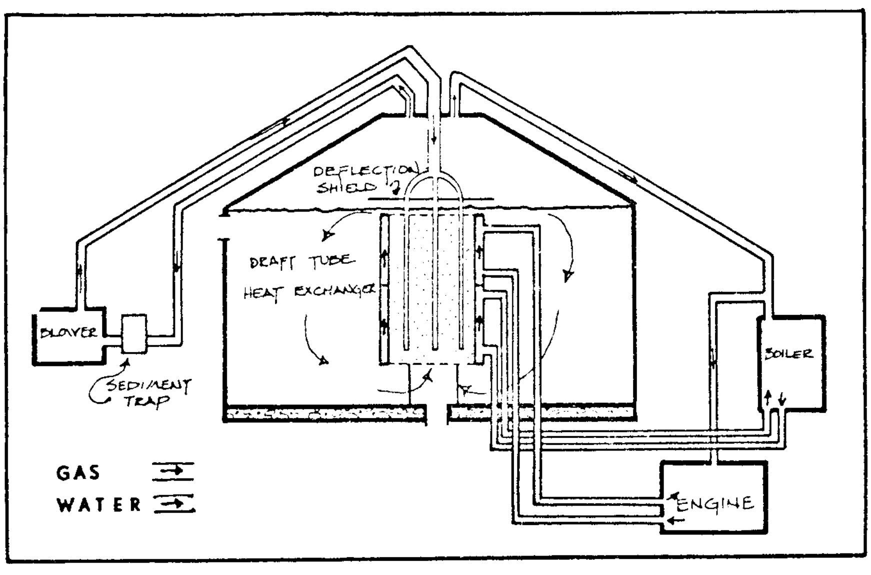


Figure 2.5
Gas Heating and Mixing System

Gas is pumped to the bottom of the draft tube located 12" from the floor of the digester. The gas is released, causing the rising bubbles to displace manure in the tube, thereby creating a pumping/mixing action. The principle is the same as that used in an aquarium air pump.

2.2.6 Heating. The digester must be maintained at 35°C (95°F) to optimize the mesophilic gas production. This is done by burning a portion of the bio-gas in a boiler which circulates hot water through the draft tube-heat exchanger in the digester tanks (Figure 2.6).

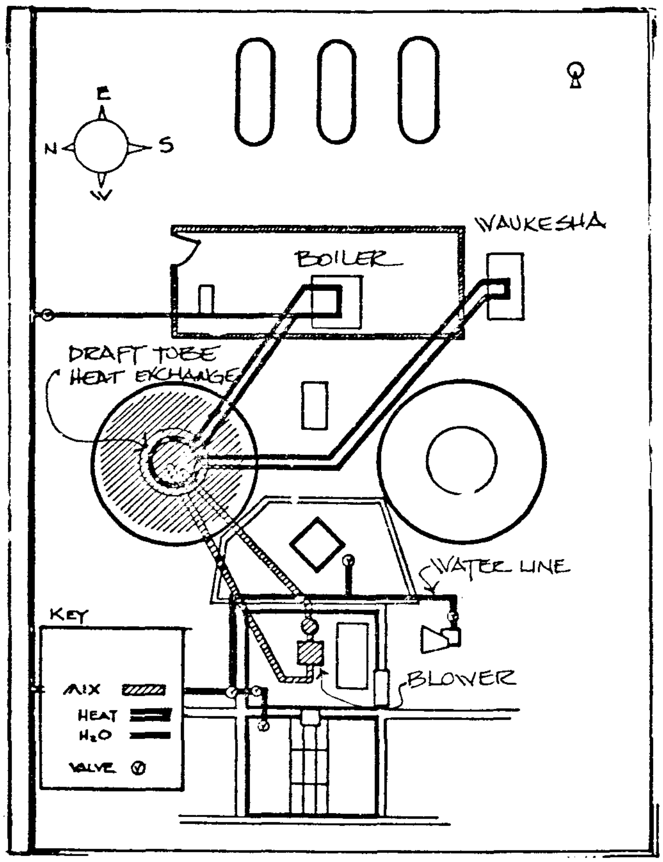


Figure 2.6
Digester Mixing and Heating System

In addition, cooling water from a Waukesha internal combustion engine can also be circulated through the draft tube-heat exchanger to maintain digester temperature.

2.2.7 Gas Handling. Gas produced in the digester is either burned in a boiler for heating the digester, scrubbed and compressed for use in the engine/generator, or flared. The system was designed to fire a boiler in an adjacent creamery. However, the gas hookup has not yet been completed (Figure 2.7).

2.2.8 Engine/Generator. An internal combustion engine with a 40kWh (peak) generator was installed as a part of the original demonstration project. The purpose of this installation was to provide emergency back-up electricity for the creamery and milking operations and to use with excess summer gas production. The engine is a natural gas engine adapted for bio-gas. Engine coolant water can be circulated to the internal draft tube-heat exchanger to provide digester heating.

The engine coolant is sufficient to maintain digester temperature under the most severe weather conditions. This increases the operating efficiency and completely supplants the boiler. However, even under optimum conditions, the efficiency of electrical conversion is no greater than 20%, making this sort of operation much less feasible than direct use of the gas produced.

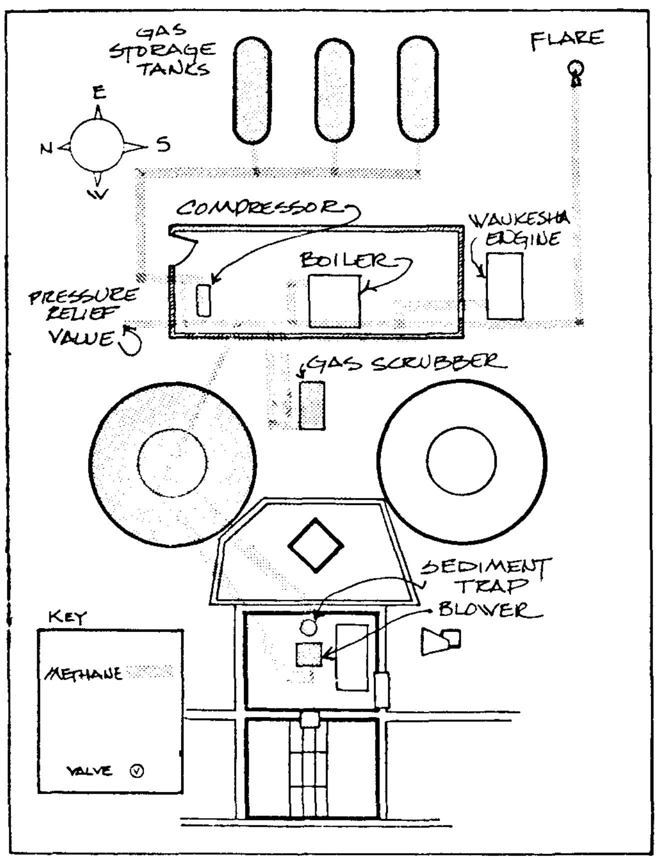


Figure 2.7

Gas Handling System

3.0 SYSTEM COMPONENT EVALUATION

3.1 Tanks

The digester tanks are an example of the integration of products from the agricultural sector into a sewage treatment technology. The reactors are two 189 m^3 (50,000 gallons) A.O. Smith Slurrystore$_{tm}$ tanks fitted with Harvestore$_{tm}$ silo roofs. These fixed-cover tanks are 25 feet in diameter and 13.5 feet high.

It became evident in the course of the design phase that products from farm applications are much less expensive than comparable products found in other sectors (industrial wholesale, sewage treatment and commercial product distributors). Harvestore tanks were chosen not only on the basis of their cost, but also on the flexibility that the dual tank configuration offered and Harvestore's "turn key" installation. The entire system was purchased from a local dealer and installed by a trained crew over a two-week period.

3.1.1 Tank Modifications. Certain tank modifications were made for their use as experimental anaerobic digesters. In addition to Harvestore's manhole covers which were added to the roof and sides of the tanks, two "thief holes" were installed on the digester roofs for obtaining samples of the digester contents from the interior of the tanks(Figure 3.1).

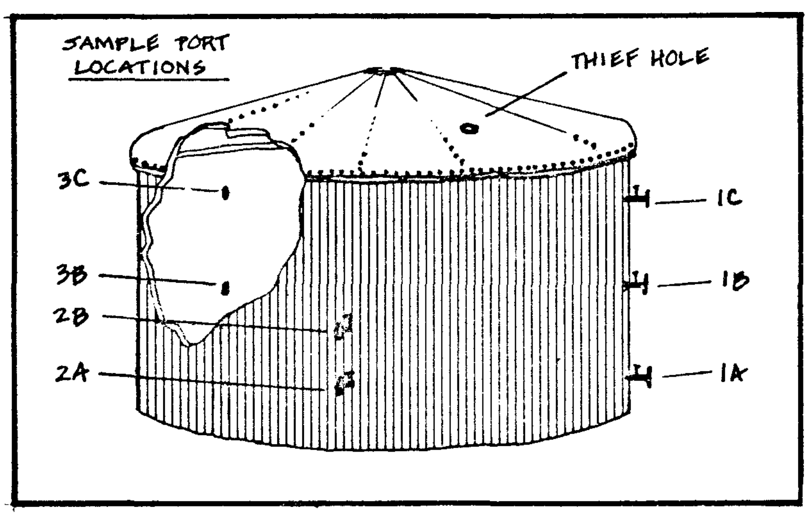


Figure 3.1
Sample Port and Thief Hole Locations

Eight side-mounted sampling ports were also installed at three levels around the perimeter of the tank to provide a variety of sampling locations. These modifications were necessary for research purposes and would not be necessary in a commercial installation.

The most significant tank modification was the addition of insulation to all exposed tank surfaces. The interior roof of the tank was sprayed with 3½" of polyurethane foam (R-21). Exterior walls were covered with 4" of Dow Styrofoam SM_{tm} (R-22), covered over with corrugated galvanized iron roofing sheets. These changed the heat loss rate of the tanks from approximately 1.7 megaJoules/hr-°C (3000BTU/hr-°F) to 81.5 kiloJoules/hr-°C (139 BTU/hr-°F).

<u>3.1.2 Tank Loading</u>. The digester tanks were sized based on receiving manure from 300 cattle units (1000-pound cow). The manure was to be loaded at 9% solids with a retention time of 17 days. Based on these assumptions, the volume needed was 378 m^3 (100,000 gallons).

Presently, all the manure received is being loaded into one 189 m^3 tank. The reasons for this are:

(1) Manure is received from only 227 cattle units.

(2) The manure is loaded at 10% total solids.

(3) The retention time has been lowered to 12 days.

<u>3.1.3 Optimum Tank Utilization</u>. In this system, as high a retention time as 17 days is not justifiable. The design of the system was based on sewage treatment engineering experiences. However, the characteristics of dairy cow manure are sufficiently different from municipal sewage to make many of the original assumptions invalid. Retention times which are considered short for sewage treatment are quite reasonable for dairy cow manure where the substrate is very stable and the emphasis is on maximizing gas production and not on maximizing waste treatment.

All of the manure now received is loaded into one tank. Jewell, *et al* (1977) reported that a ten-day retention time is optimum for a high rate, complete mix mesophilic system. Reducing our retention time from its present 12 days to 10 days would allow us to load the entire resources from 200 cows (260 cattle units) into a single tank. Consequently, our double tank system is correctly sized for a 400-cow dairy (520 cattle units).

In rigid tank digester systems, the reactor tanks represent a significant capital cost. Such systems should be designed to load the manure at a high percent solids with a ten-day retention time in order to avoid paying for unneeded digester volume.

3.2 Influent Handling and Mixing

3.2.1 Manure Handling and Preparation. Each morning, manure is removed from the loafing shed by a tractor with a rear-end scraper. It is scraped out a concrete aisle to a grate over the influent tank. Approximately 10 ft^3 of sawdust and woodchips which are used for bedding in the loafing shed is mixed with the manure each day. Since manure is scraped only once a day and includes bedding material, it often contains thick clods of manure and is drier (14.5% - 16% total solids) than a pure, continuously scraped substrate. This increases the energy needed for thorough influent mixing.

The manure and water added to the influent tank are mixed with a 10hp Vaughan chopper pump with a 2" iron pipe by-pass. This by-pass is attached to the pump discharge and aimed at the surface of the influent. Another 3" flexible hose by-pass moves in a snakelike action across the surface of the manure to draw more of the tank's contents into the mixing stream.

3.2.2 Influent Solids. Loading began in August 1977 at 4% solids and gradually was increased to 10% solids. The chopper pump thoroughly mixed 4 to 8% solids in 30-45 minutes with a minimum of operator attention. At 10% solids, mixing time has increased to one to two hours, and the operator is required to pull substrate from the corners and bottom of the tank with a long pole. This higher percent solids, however, has improved other aspects of the system operation. Formerly, it was necessary to flush out all effluent lines using a garden hose and high pressure water. Since increasing the % solids loaded, most of the effluent clogging problems and scum formation in the effluent have been eliminated. In addition, solids stratification inside the digester decreased (see Section 3.5.3).

The influent heating demand is also reduced since the volume of influent water which must subsequently be heated to 35°C is reduced. For example, the influent heating demand of slurry loaded at 6.45 kg volatile solids (VS) per cubic meter per day (.4 pounds VS/ft^3-day) at 10% total solids is 1.38×10^9 Joules/day (1.31×10^6 BTU/day). The same loading rate at an 8% total solids is 1.73×10^9 Joules/day (1.64×10^6 BTU/day), an increase of 25%. This represents an additional 7,075 m^3 (250,000 ft^3) of bio-gas per year (at 80% boiler efficiency), which would be expended to bring the influent to a digester temperature of 35°C.

Likewise, a loading rate at a higher % total solids will decrease the reactor volume needed to handle a given amount of substrate. In our case, loading the resource from 260 cattle units at 10% total solids with a ten-day retention time requires a volume of 176 m^3 (6250 ft^3). The same amount of manure loaded at 8% solids with a 10-day retention time requires a volume of 212.4 m^3 (7500 ft^3).

3.2.3 Influent Mixing Specifications. The benefits of loading a high percent solids are decreased volume and decreased energy demands. The problems associated with it are influent mixing and loading. These problems are not so severe when dealing with a pure substrate. However, the addition of bedding introduced complications which must be taken into account.

In our system using the Vaughan pump, a uniform mixing of up to 12% solids has been achieved, but complete mixing of the as-received manure (14.5%-16% solids) is unlikely with present equipment. Loading of influent which is greater than 11% solids has not been possible.

This particular design flaw is the result of inadequate experience handling dairy manure substrates. The system was designed for 9% continuous loading and 17-day retention time. The result was undersized pumps and oversized tank capacities. The need for accurate engineering must be underscored and subsequently the need for accurate data by which to design these systems is essential before any large scale development can be achieved.

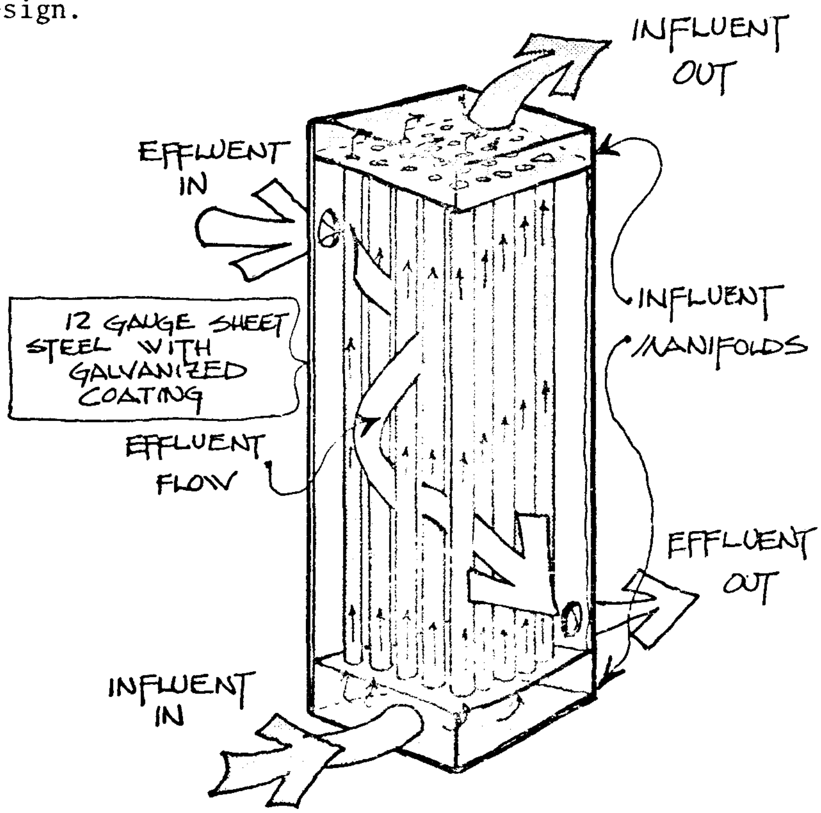
3.3 Heat Exchanger and Loading System

3.3.1 Heat Exchanger Design. Preliminary analysis of the heating requirements for the digesters at Monroe indicated that a major source of heat loss and subsequent gas consumption would be associated with daily loading of fresh manure (Ecotope Group, 1975). The displacement of heated manure with ambient fresh manure was estimated to require 89% of the gas consumed in the boiler to maintain digester temperature. Additionally, in a system with a short retention time, the loading of cold manure can cause noticeable temperature fluctuations in the digester contents.

The preliminary design criteria called for a heat exchanger which was capable of recovering 40% of the heat lost through loading. The first design was to build a series of aluminum pipes in the effluent holding tank so that cold influent could be pumped through the warm effluent. The design was abandoned because of its difficulty in construction, probability of clogging and fabrication expense.

A consultant was hired and extensive design and testing were undertaken. Based on empirical test of heat exchange rates between two streams of Monroe cow manure, a new vertical, counterflow heat exchanger was constructed (Reichmuth, *et al*, 1977). This heat exchanger was designed to recover 58% of the heat from the effluent and transfer that heat to the incoming stream of fresh manure. Fresh manure was to be pumped through 25 - 3" tubes attached to equalizing manifolds. Displaced effluent was to flow around the outside of the tubing at a flow rate of 0.25 *l*/sec (4 gpm) to transfer heat through the tubing walls to the incoming 10°C (50°F) manure. Greater than 50% heat exchange was possible through the estáblishment of a gradient within the shell and tube counterflow design.

Figure 3.2
Influent/Effluent
Counterflow
Heat Echanger



<u>3.3.2 Loading Requirements</u>. The new design required a very slow rate (4 gpm). The already acquired Vaughan manure chopper pump was rated at 200 gpm. After careful comparison of diaphragm and progressive cavity-type pumps, it was decided that the diaphragm pump was more suitable. This decision was based on three factors:

(1) Potential damange from rocks in the manure.

(2) $1500 savings in capital cost.

(3) Ease of maintenance.

However, an ITT Marlow diaphragm pump which was purchased has proven to be a miserable failure. Even though it is rated to handle 10% solids, the size of the bedding particles prevents the pump from functioning. Wood chips lodge on the seats of the ball-type check valves which are essential to the pump's operation, making the pump inoperable. This has made it impossible to test or evaluate the heat exchanger since a continuous loading rate was not possible without this pump (Figure 3.3)

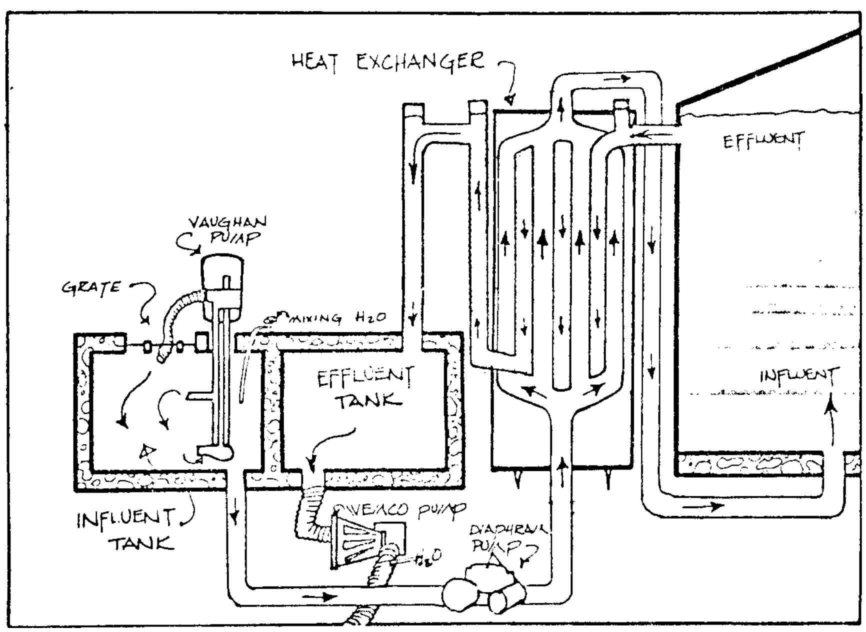


Figure 3.3
Loading Through Heat Exchanger

Under current operating conditions, the Vaughan pump loads the digester at the high flow rate, by-passing the heat exchanger. This results in subtantial heat losses and digester temperature fluctuations which underscore the importance of a working influent/effluent heat exchanger system (Figure 3.4).

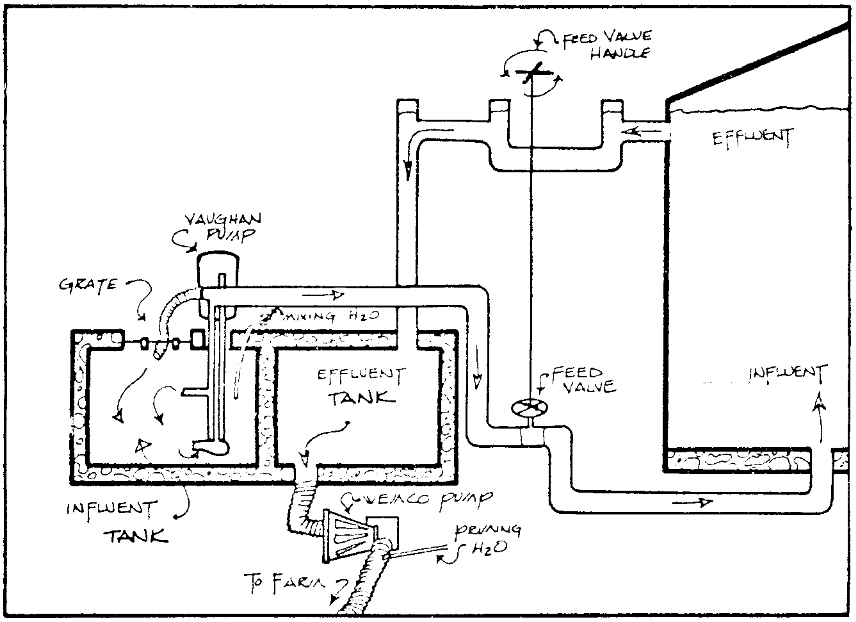


Figure 3.4
Loading, By-Passing the Heat Exchanger

<u>3.3.3 Heat Exchanger Operation</u>. The heat exchanger was tested in February of 1976 by using the Vaughan chopper pump to pump a 3% slurry into the south digester. During this period, intermittent loading and use of the heat exchanger resulted in severe clogging of the heat exchanger. A subsequent failure in one of the rubber connectors caused a short circuit in the system and the system was abandoned.

In October 1977, the heat exchanger was opened for inspection and subsequent testing led to the replacement of the segmented aluminum tubes with thin-walled PVC pipes of the DMV type. These indicated a reduced performance from 58% to 50% heat exchange (Ecotope Group, January 1978).

All attempts to test the refurbished heat exchanger have been unsuccessful. The diaphragm pump is a total failure at the high solids (10%) loading. The 10 hp Vaughan pump cannot overcome the head required to move manure through the heat exchanger.

3.3.4 Alternatives. Based on the current wisdom and experience with the system, it appears that the following actions would alleviate the problems. They are described in the order they should be applied.

3.3.4.1 Reduction of plumbing restrictions. The current influent plumbing should be modified to use flexible hose connections to the top outlet of the heat exchanger and the digester should be loaded through an existing roof-mounted thief hole. This eliminates three elbows and about 40 feet of 4" pipe. Previous experience on site with a centrifugal pump clearly indicates that rigid plumbing and elbows with attendant head losses can be a major cause of pumping malfunctions.

3.3.4.2 Change pumps. Current loading of high solids indicates a pumping and mixing limitation. A progressive cavity pump or a ram-type pump with positive closing check valves would alleviate the slow rate pumping problem. At high solids, the Vaughan chopper pump might be sufficiently fitted with a gate valve by-pass to allow constant mixing and slow loading rates through the heat exchanger. This might require a larger motor on the Vaughan pump capable of using up to 30 hp.

3.3.4.3 Other designs. The issue to be solved here is significant and potentially the most important aspect of increased performance for digesters. If the manure-to-manure counterflow proves unsuccessful, then a water or glycol-type fluid could be used to move heat from the effluent tank to the influent. There is even some reason to consider the use of liquid-to-liquid heat pumps if the less costly solutions are not adequate.

Increased gas production is a matter of increased loading rate. Increased loading rates require decreased retention times and subsequent high rates of heat loss through high volumetric changes of liquid. This is even more critical with thermophilic 5-8 day retention times where temperature differentials are often double those for mesophilic.

3.4 Mixing System

The mixing requirement in the original design specifications were based on experience in municipal sewage treatment. With sewage, the substantial mixing is required to prevent "scum" formation which in time would inhibit the functioning of the digester. To avoid scum formation problems, the system was designed as a complete mix system with provisions for constant mixing.

3.4.1 Mixing System Design. Gas recirculation mixing was chosen for its ease of installation and for its integration with the internal heating system. A draft tube is employed to aide in dispersing the slurry. The draft tube is also a heat exchanger, having concentric walls which form a water jacket (Figure 3.5). The inside diameter of the draft tube is 860 mm (34") and the outside if 910 mm (36").

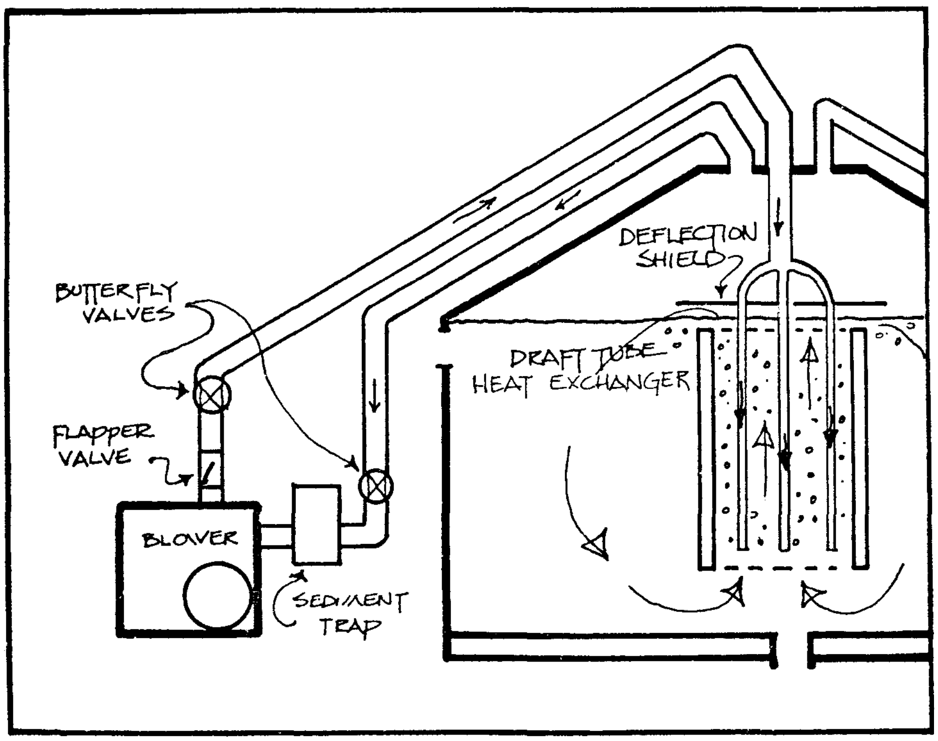


Figure 3.5
Gas Recirculation Mixer

Gas is pumped through four 50mm (2") galvanized iron pipes (GIP) supported by a deflector plate at the top of the draft tube. These pipes are connected to a 75 mm (3") CPVC gas line from a Roots-type blower operating at 5psi (34,00 N/m^2). The pipes extend to the bottom of the draft tube located 300mm (12") from the floor of the digester. The gas is released, causing the rising bubbles to displace manure in the tube, thereby creating a pumping/mixing action as with an aquarium pump.

3.4.2 Blower Operation. During the first five months of operation in 1976, the blower was run continuously. The project was then shut down and the blower sat idle for a year. When operation resumed at the Monroe facility, the blower was thoroughly overhauled. However, continuous operation stressed it more than was anticipated and after twenty days, the blower lost a rear bearing on one of the compressor lobe shafts. After repair and installation, the factory representative required that oil be changed in the blower on a weekly basis. (Figure 3.6)

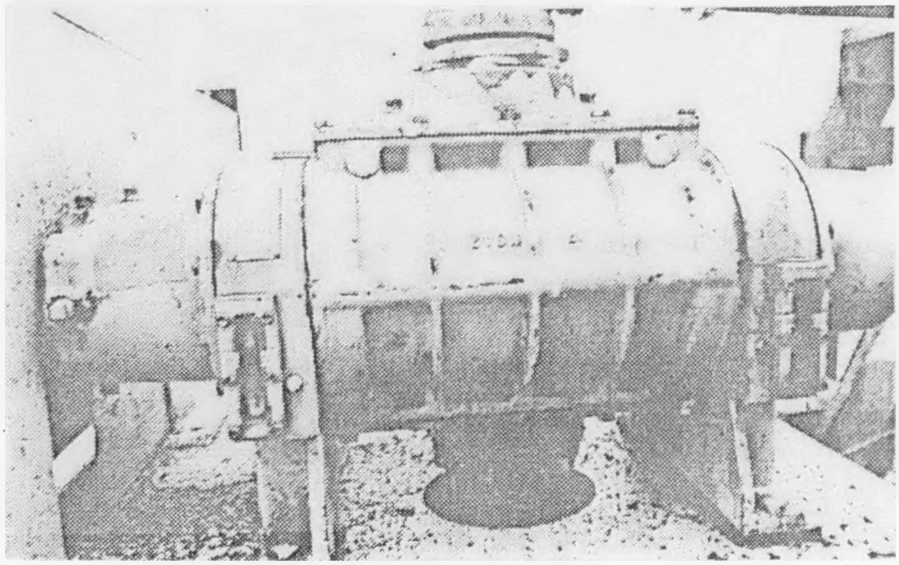


Figure 3.6
Roots-Type Recirculation Blower
(6psi @ 270 cfm)

To evaluate the internal energy demands of the system, a watt meter was installed to monitor the electrical consumption of the gas recirculation mixer. Under continuous operation, daily consumption was 180 kWh/day. This was almost 90% of the total electrical demand of the system operation. The high energy demand and the equipment stress associated with continuous mixing led us to investigate whether a complete-mix system could be retained with intermittent mixing. Work by Hein *et al* (1977) and Converse indicated that this might be the case.

3.4.3 Mixing Studies. Baseline mixing studies were performed to determine if any stratification was occurring with continuous mixing (see Table 3.1). Samples were taken from ports at three levels around the perimeter of the tank (see Figure 3.1). Samples of the top and bottom of the interior of the tank were obtained through the thief hole. Samples of the perimeter on January 21 showed no stratification. However, stratification was evident on samples taken from the interior.

Intermittent mixing began on February 22. The blower was cycled on for 15 minutes and off for 15 minutes. Subsequent tests on the perimeter have shown no development of stratification. Tests on the interior indicated a decrease in the degree of stratification. This decrease was most likely due to an increase in the percent solids in the tank which has occurred since the feed was raised from 8% to 10%. Materials stay in suspension better at higher percent solids, as has been evidenced by small rocks in the effluent test.

Mixing was again decreased on April 5 to ten minutes on and 20 minutes off. Tests run after three weeks showed no evidence of stratification in the interior or along the perimeter. Beginning May 11, the blower was cycled to 10 minutes on and fifty minutes off. Tests run on the First of June showed no stratification along the perimeter. However, there appears to be vertical stratification in the interior.

Table 3.1

Sample Results for Mixing Studies

Samples from Perimeter

		-- Constant	Mixing --			----- 50%	Mixing ----			33% Mix		* ----- 17%	Mix ------		
	day:	1-21-78		2-18-78		3-4-78		4-4-78		4-29-78		*6-1-78		6-10-78	
	sample port #	%TS	%VS	%TS	%VS	%TS	%VS	%TS	%VS	%TS	%VS	%TS	%VS	%TS	%VS
TOP	1C	7.4	81.5	8.2	82.1	8.2	81.4	8.0	80.9	8.1	81.9	7.3	82.7	7.87	80.9
	3C	7.5	81.2	8.4	91.8	8.2	81.2	8.0	81.2	8.2	92.2	7.6	81.0	7.82	81.3
MIDDLE	1B	7.2	81.1	8.4	82.5	7.8	81.0	7.9	80.5	7.9	81.7	7.5	80.3	7.87	81.1
	2B	7.2	82.1	8.3	82.8	8.2	81.3	8.1	81.3	8.1	82.0	7.3	80.3	8.10	31.4
	3B	7.1	81.3	8.3	82.6	-	-	7.9	81.1	8.2	82.2	7.3	80.4	8.17	31.7
BOTTOM	1A	7.4	81.4	8.3	82.5	8.2	81.0	8.2	81.7	8.7	82.5	7.5	80.7	7.87	81.2
	2A	7.5	82.4	6.3	81.2	8.5	81.0	7.9	80.7	8.0	81.9	7.5	81.0	7.90	31.2

Samples from Interior
of Digester Tank

	-- Constant	Mixing --			----- 50%	Mixing ----			33% Mix		----- 17% Mix ------			
day:	1-25-78		2-14-78		3-4-78		4-4-78		5-3-78		*6-1-78		6-10-78	
thief hole:	%TS	%VS	%TS	%VS	%TS	%VS	%TS	%VS	%TS	%VS	%TS	%VS	%TS	%VS
top	8.5	82.7	9.0	84.0	8.4	81.9	8.8	82.2	8.4	82.5	8.7	81.9	8.6	81.0
bottom	8.0	82.6	8.5	83.1	8.1	81.0	8.6	91.9	8.4	81.8	7.9	81.0	8.2	80.5

* *Sample taken after water leak from heat exchanger diluted tank contents*

It was unclear whether this stratification was due to the reduced mixing or to a decrease in the percent total solids of the digester contents. This decrease was caused by a leak in the boiler heat exchanger in late May which released large quantities of water into the digester over a ten-day period. This decreased the % solids from 8.1 to 6.9. The leak has been remedied and the percent solids of the digester contents are contining to rise.

Tests run later in June 1978 showed a higher % solids in the digester. There is still no perimeter stratification and stratification of the interior has decreased. This appears to indicate that the determining factor in maintaining a well-mixed system with intermittent mixing is the percent solids of the digester contents and not the amount of mixing. We will continue to decrease the amount of mixing throughout the next year to attempt to determine the lower limit of mixing necessary to maintain a healthy system.

Continuous mixing not only has a high energy demand and is hard on equipment, it is obviously not necessary. Consequently, to save on the capital cost of a system, it would be a benefit to avoid buying a separate piece of equipment to be used only occassionally. Employing multiple-use equipment such as a PTO from a tractor could be preferable. Certainly the mix equipment installed should enable intermittent mixing. Perhaps an in-tank mechanical mixer would better serve this specification.

3.5 Digester Heating

Digester contents are maintained at 35°C by use of an internal hot water heat exchanger. The heat exchanger is cylindrical in shape and doubles as a draft tube. Hot water can be fed into the heat exchanger from either a boiler or from the coolant system from the internal combustion engine used to produce electricity (Figure 3.7).

3.5.1 Boiler Heating. The system boiler is a National 209 Series with a rated output of 396 megaJoules (375 x 10^3BTU). Biogas is burned directly to produce 54°C (130°F) water which is pumped into the lower section of the heat exchanger (Figure 3.8). Operation of the boiler is controlled by a thermo-

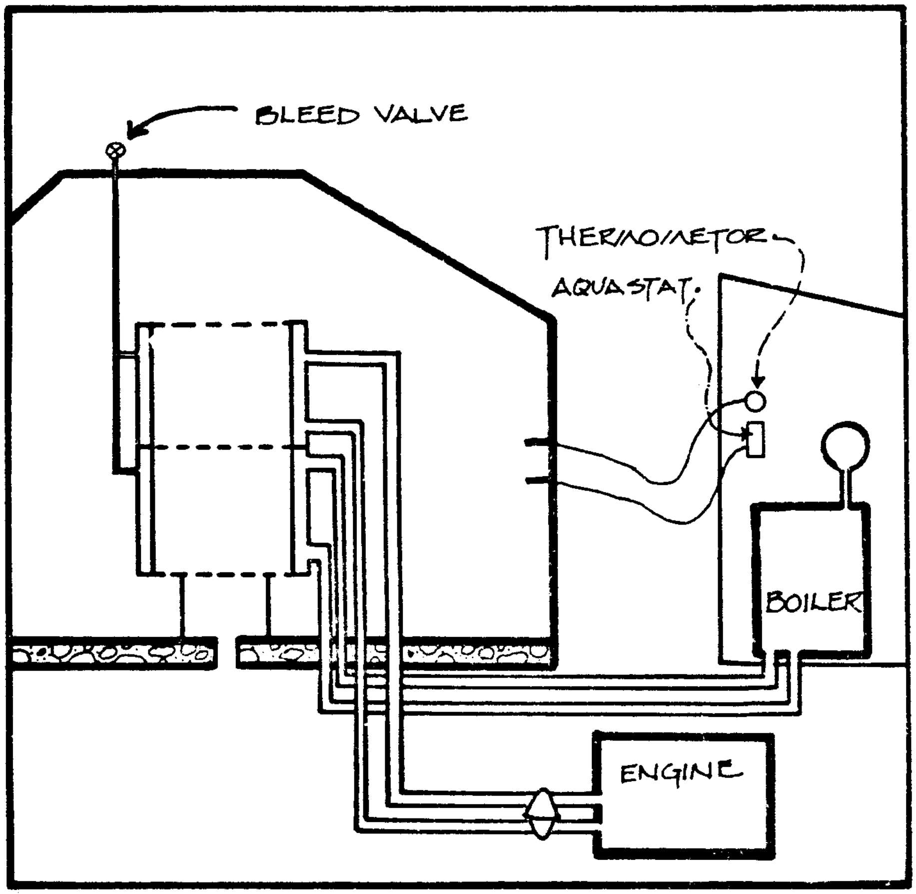
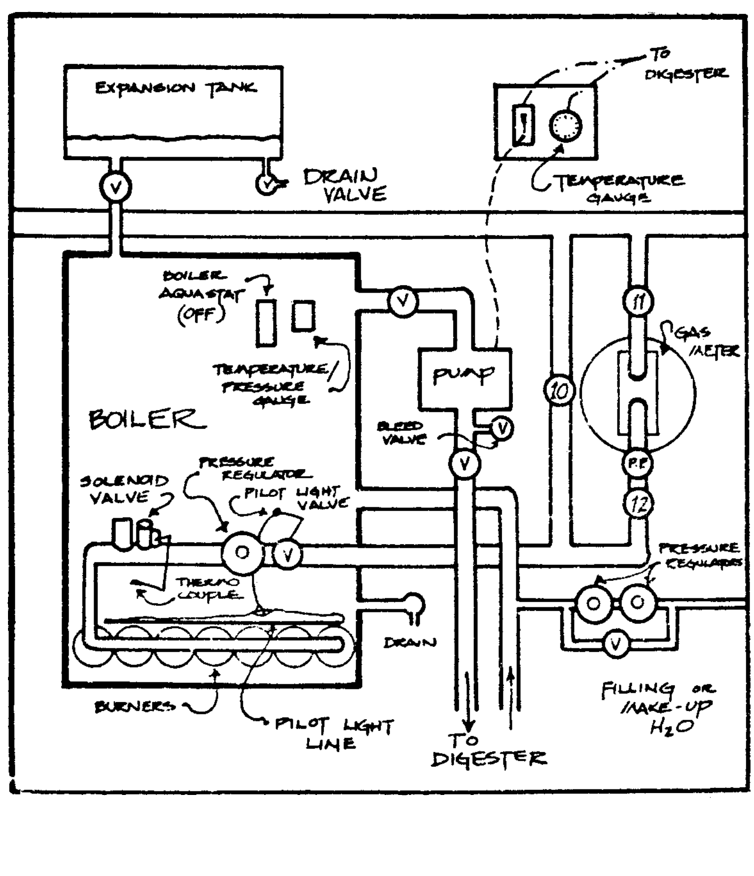


Figure 3.7

Digester Heating System

Figure 3.8

Boiler Heating System



static valve. However, the present digester aquastat has been unable to control digester temperature to tolerances closer than ±3°C (4°F). This has resulted in erratic boiler gas consumption and less than optimum digestion conditions. Digester temperature has been known to fluctuate as much as 5° over a two-day period.

3.5.2 I-C Engine Heating. When the I-C engine is being operated, waste heat from the coolant system can be circulated through the upper portion of the heat exchanger. The use of waste heat has supplied all heating demands of the digester even during the cold months. This improves the overall efficiency of the use of the I-C engine since it allows for the utilization of a portion of the energy usually lost as waste heat.

3.6 Gas Handling

The gas handling components of the Monroe system were modified little from standard sewage treatment gas handling. Consequently, it proved to be one of the most expensive aspects of the system (Figure 3.9).

3.6.1 Design Criteria. According to the original design, gas was to be:

(1) Burned directly with the boiler for heating the digester;
(2) scrubbed and transported to the Farm's creamery to be used to produce hot water; or
(3) burned in an internal combustion engine to produce electricity in emergency situations.

It was decided during the design phase that a one-half day storage should be available to buffer the system and provide gas to meet peak electrical or gas requirements.

3.6.2 Storage tanks. Three 3.79 m^3 (1,000 gallon) propane tanks are used for storing bio-gas. These tanks have a working pressure of 1.65 megaPascals (240 psi) and are capable of storing 61.73 m^3 (2,180 ft^3) of bio-gas each. A Corken two-stage compressor with a 2hp motor was obtained as part of the storage system. Gas which is compressed first goes through a hydrogen sulfide scrubber. As yet there has been no noticeable corrosion problems with the compressor.

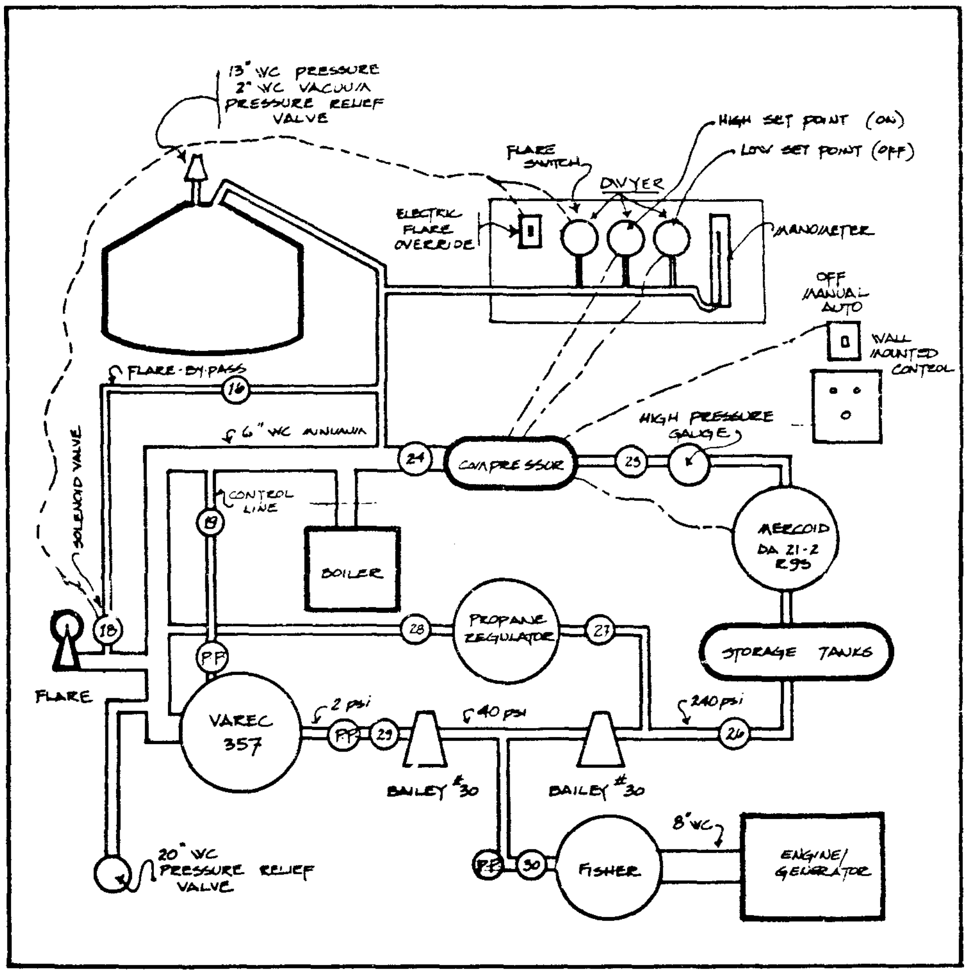


Figure 3.9

Gas Handling System

3.6.3 Gas Safety Equipment. Varec gas safety equipment was used throughout the system. This included the use of safety alarms, pressure relief valves, a repressurizer, flame traps, and drip traps.

Although these types of equipment are essential for the safe operation of a digester, using safety equipment made for municipal sewage treatment plants added almost 5% on to the cost of the system.

3.6.4 Pressure Control. The pressure system was designed within the constraints of the upper and lower pressure limits of the tank. The tank was pressure tested to 4.9 kiloPascals (20"WC). Pressure relief valves were set at .5 kPa (2"WC) vacuum and 2.7 kPa (11"WC). The boiler operates between 1.5 - 1.7 kPa (6"-7"WC) if heat is needed. The compressor operates between 1.7 - 2.4 kPa (7"- 9.5"WC). The compressor is activated when the gas pressure in the digester reaches 2.4 kPa (9.5"WC). The compressor pumps gas into the storage tanks until storage tank pressure reaches 1.65 MPa. If that pressure is reached, the pressure in the digester is allowed to reach 2.7 kPa (11" WC) and the flare is activated. This reduces the pressure in the digester to 2.5 kPa (10"WC) automatically.

If the pressure goes above 2.7 kPa (11"WC), a pressure relief valve on top of the digester will release gas. There is also a back-up pressure relief valve set at 4.0 kPa (16"WC). When both of these relief valves fail, tank contents are forced out through a 6" PVC overflow on the effluent line.

Because of the relatively narrow pressure bands in which the equipment operates, there was a need for very sensitive pressure switches. There are now a series of Dwyer pressure switches which are used to control the compressor and flare. These have proved adequate for control within the small pressure fluctuations.

3.6.5 Wet Gas Handling Problems. Handling wet gas presented numerous problems with water accumulating and freezing in the lines. Gas meters obtained from the local gas utility must be drained daily to prevent water accumulation. All gas meters were moved inside the boiler room to prevent freezing during the winter. A valve which has a constricting orifice was a site of frequent freezing and has been well-insulated.

All gas lines had to be insulated and pressure relief valves must be checked regularly in winter for freezing. Twice during the past winter, both the gas lines and pressure relief valves froze at night, causing the manure to be forced out through an overflow on the effluent line. This system failure suggests that the overflow effluent design provides an emergency back-up to the other pressure relief and insures continuing digester safety.

3.6.6 Gas Utilization. Gas is now being burned in the boiler without first being scrubbed for hydrogen sulfide. The only noticeable effect has been that it is necessary to clean the jets every six months. The I-C engine has not been run enough to determine if there are any corrosion problems. Bio-gas is also being used in the lab/office trailer for burners, heating and for cooking. The hook-up to the creamery boiler has not yet been made and presently all gas which is not used for heating the digester in the trailer is being flared.

3.7 Engine/Generator

An internal combustion engine with a 40kW (peak) generator was installed as a part of the original demonstration project. The purpose of this installation was to provide emergency back-up electricity for the creamery and milking operations and to use with summer excess gas production. The engine is a Waukesha VRG 310 natural gas engine with a dual fuel Impco Model 200 carburetor. The engine is directly coupled to a Kato generator. Engine coolant water can be circulated to the internal draft tube-heat exchanger to provide digester heating.

Table 3.2 describes the operation of the engine generator during the initial shakedown in December 1977.

Table 3.2

I-C Engine/Generator Production Efficiency

date	gas consumption m^3	(ft^3)	hours run	electrical production MJ	(kW/hr)	conversion efficiency*
December						
12	128.64	(4543)	7.8	392	(109)	13.6%
13	109.53	(3868)	6.6	205	(57)	8.3
14	177.71	(6267)	12.5	454	(126)	11.4
15	120.86	(4268)	7.4	288	(80)	10.7
16	108.26	(3823)	7.5	270	(75)	11.2
17	84.75	(2993)	5.7	212	(59)	11.2
18	9.29	(328)	.6	18	(5)	8.7
19	103.44	(3653)	7.4	306	(85)	13.2
20	118.28	(4177)	10.3	317	(88)	12.0
21	339.58	(11992)	23.2	756	(210)	10.0

*This figure assumes the energy content of the gas to be 22.354 MJ/m^3. (600 BTU/ft^3)

The electrical conversion efficiency has been very low -- on the order of 11%. With all electrical equipment on site operating, we can draw only 35 to 40 amps. The generator capacity is 40 kWe or 83 amps at 480 volts. The engine and generator perform at less than maximum efficiencies (23% and 90% respectively) if they are not run at rated horsepower and full electrical load. One possible solution to inadequate loading is to sell power to the public utility.

The engine coolant is sufficient to maintain digester temperature under the most severe weather conditions (Figure 3.10). This was confirmed during its operational period in December 1977 and January 1978. This increased

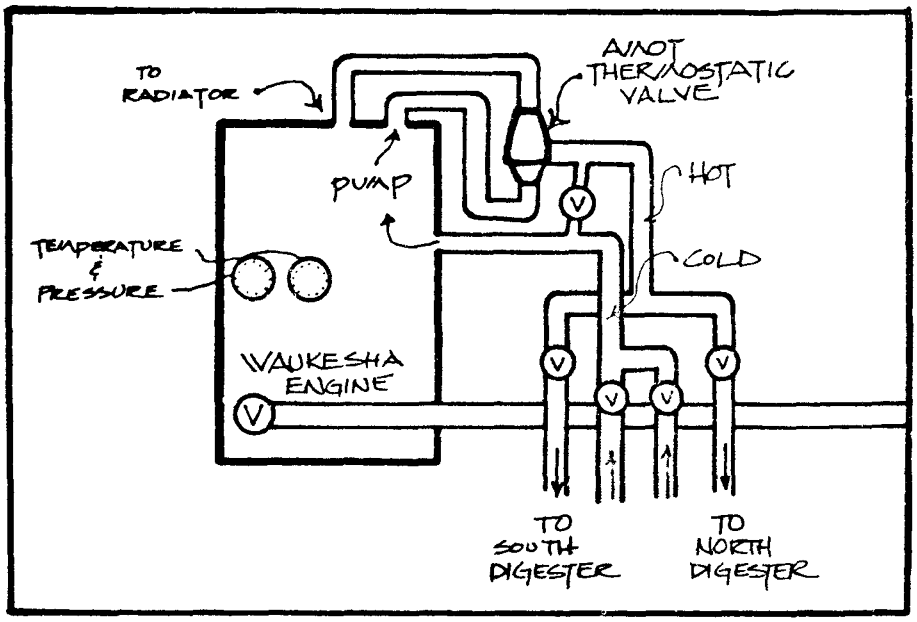


Figure 3.10
Waukesha Coolant Used for Digester Heating

the overall efficiency of the fuel consumption since it replaced the need for boiler heating. This heating supplement has been estimated at about 1500 MJ (1.42mmBTU)daily for December and January (see Section 5.0). Taking December 16, 1977 as a representative case, the overall efficiency of electrical production and heat recovered would theoretically be as follows:

$$\frac{270 \text{ MJ(electricity)} + 1500 \text{ MJ(heat)}}{2700 \text{ MJ (I-C gas usage)}} = 73\%$$

This high efficiency is attributable to the high January heating demand and because the Waukesha was able to supply all the digester's heating needs during the 7.5 hours it was run each day. Had the engine been run for 24 hours, not all of the waste heat could have been utilized. If run constantly, the efficiency should not exceeed 64% in Janaury. In the summer months, when even less of the waste heat is need for digester heating, the overall efficiency will fall to 39%.

Presently, there is not sufficient instrumentation on the Waukesha coolant system to allow accurate measurement of the engine's efficiency at heating the digester. This instrumentation will be installed during the 1978-79 operating year and a more thorough analysis can then be performed.

4.0 BIOLOGICAL SYSTEMS

4.1 Laboratory and Testing

A laboratory was established at the Monroe facility to monitor the health of the digester and to note the impact of varying loading and mixing regimes on biological activity. The substrate has proven itself to be remarkably stable and there have been no serious signs of stress, even with decreased mixing, temperature fluctuations and high loading rates.

At the beginning of the project, digester contents were tested daily for pH, acidity, alkalinity, total volatile acids, percent total solids (%TS), and percent volatile solids (%VS). Influent and effluent were tested for pH, %TS, and %VS. Once the system stabilized, the results of the tests of digester contents became quite constant and testing frequency was reduced to twice a week. Influent and effluent samples are still tested daily, since that data is necessary for determining the mass balance of the system.

All tests were run according to the procedures of Standard Methods. The only modification was in testing for total volatile acids. Pressure with CO_2-free air was substituted for the use of suction in drawing the acidified sample through the silicic acid column (pg. 538, 12th ed. Standard Methods). See Figure 4.1

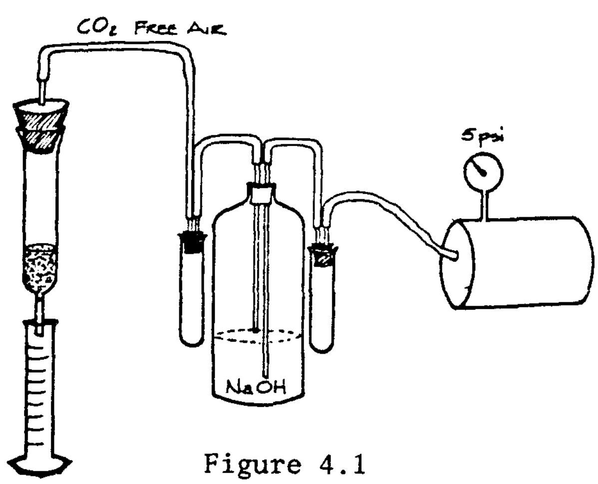


Figure 4.1
Volatile Acid Test with CO_2-Free Air

4.2 Digester Start-Up

Loading of one of the 50,000 gallon reactors at Monroe began on August 30, 1977. The digester was batch loaded over a five-day period. Manure mixed with sawdust bedding was scraped into the influent tank, diluted to four percent solids and pumped into the digester. The digester was then heated. The contents were tested daily for pH, acidity, alkalinity and total volatile acids.

The digester stabilized after a 30-day acclimation period (Figure 4.2). The contents followed the expected pattern of a rise in TVA with the consequent low pH, low alkalinity and high CO_2 content of the gas. The substrate began to recover on September 27 with no chemical addition for pH adjustment. By October 1, the TVA had fallen to less than 700 mg/liter. The alkalinity was greater than 3500, pH had risen to 7.2, and CO_2 content of the bio-gas had fallen to 26%.

4.3 Loading Rate

The originally designed loading schedule for the digester was developed by an experienced sewage treatment plant operator (Table 4.1). However, the increased gas production which followed each increase in loading rate and the absence of any biological stress led to increasing the loading rate more rapidly than originally planned (Table 4.2).

The planned final rate of 4 kg VS/m^3reactor (.25#VS/ft^3reactor) at 8% solids was reached in seven weeks instead of the planned twelve weeks. The loading rate would have continued to be raised, but numerous operational problems associated with winter freezing and flooding were encountered. A decision was made to hold the loading rate steady until those problems were resolved. In January, the loading rate was increased to 4.8 kg VS/m^3 (.3#VS/ft^3)/day loaded at 10% solids. The change in the % solids had a large impact on the loading procedures, but neither the increase in the loading rate nor the increased % solids had an adverse biological impact.

The loading rate was raised to its present level of 6.4 kgVS/m^3 (.4#VS/ft^3) per day with a retention time of 12 days in late February. This represented all of the substrate available from about 173 cows. The loading rate will continue to be raised as the milking herd size is increased to its proposed maximum of 200 cows.

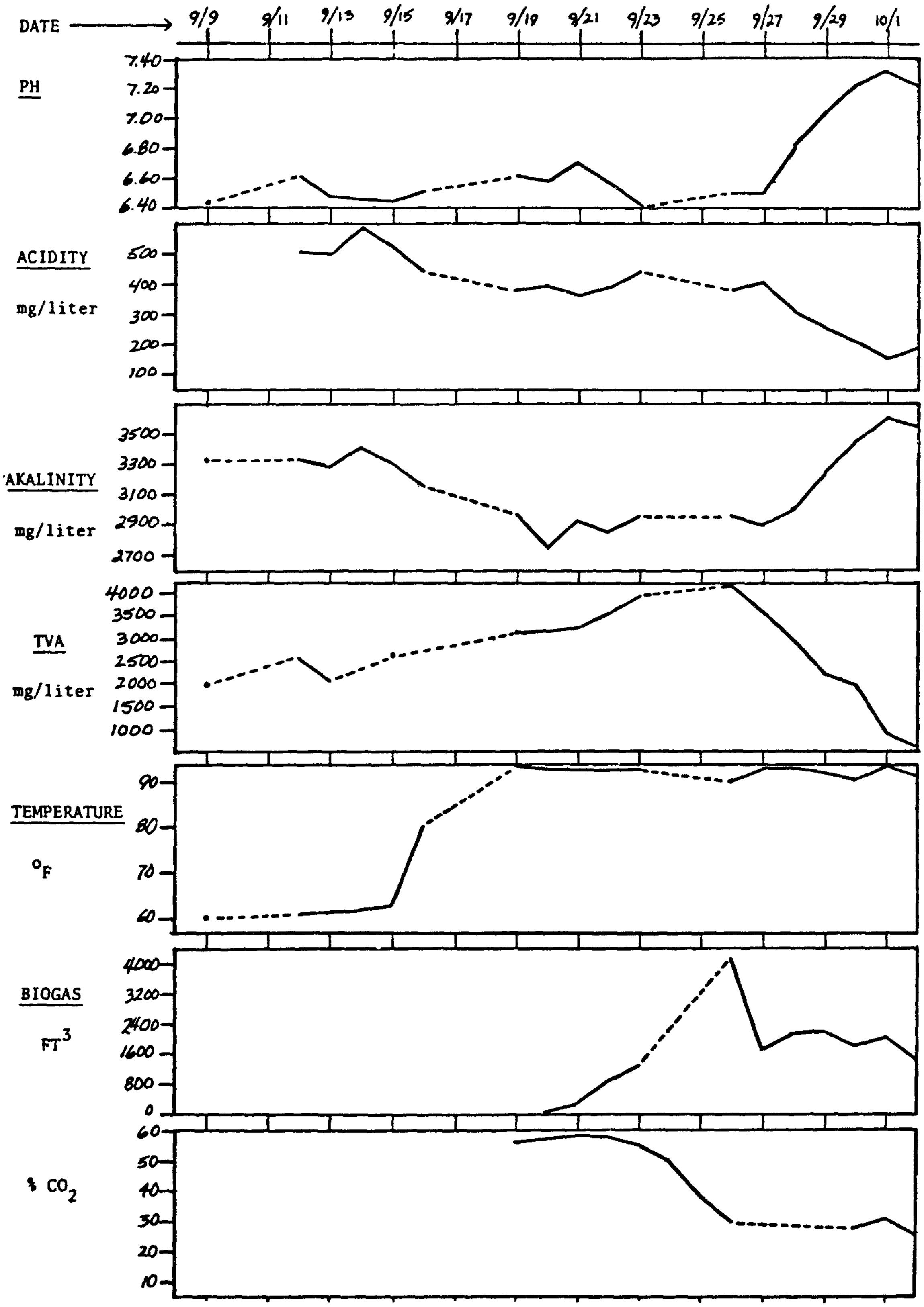


Figure 4.2

Start-up Data for Monroe Digester
September 1977

Table 4.1

Planned Loading Rate Schedule

Period of time	Loading Rate VS per day reactor kg/m^3	Loading Rate VS per day reactor #/ft^3	% Total Solids	Reactor Detention Time (days)
30 days	1.6	0.1	4%	19.7
30 days	3.2	0.2	6	14.8
30 days	4.0	0.25	8	15.7

Table 4.2

Actual Loading Rate Schedule

Period of time	Loading Rate VS per day reactor kg/m^3	Loading Rate VS per day reactor #/ft^3	% Total Solids	Reactor Detention Time (days)
one month acclimation	1.6	.1	4%	19.7
14 days	2.6	.16	6	18.5
7 days	3.5	.22	6	18
60 days	4.0	.25	8	16
30 days	4.8	.3	10	16
7 days	5.3	.33	10	15
present rate	6.4	.4	10	12

4.4 Biological System Performance

Biological performance of the system has been relatively steady throughout the year despite changes in the loading rate. Retention time has decreased from 18 days in October to 12 days beginning in late January. The percent volatile solids reduction has decreased slightly from $\overline{25.5}$% in October to $\overline{22.6}$% at the 12-day retention time. (Table 4.3). However, the amount of gas produced per volatile solids destroyed has steadily risen

Table 4.3

Biological Parameters of Digester System

DATE	LOADING RATE			% V.S. REDUCTION	BIOGAS PER V.S. DESTROYED		BIOGAS PER V.S. ADDED		BIOGAS PER CATTLE UNIT	
	kg VS/m^3-reactor day	lb VS/ft^3-reactor day	cattle units/day		m^3/kg VS	ft^3/lb VS	m^3/kg VS	ft^3/lb VS	m^3	ft^3
10-10	2.95	.180	88.9	21.8	.77	12.26	.17	2.70	1.1	38.8
10-17	3.97	.248	136.8	29.0	.61	9.80	.17	2.80	1.0	35.3
10-24	3.45	.216	126.0	51.0	.36	5.77	.18	2.88	.9	31.8
10-31	3.79	.237	143.4	none	none	none	.18	2.88	.9	31.8
11-7	3.30	.206	118.3	32.0	.59	9.45	.19	3.04	1.0	35.3
11-14	3.77	.235	135.1	20.0	.88	14.15	.20	2.83	.9	31.8
12-5	4.06	.253	144.2	28.0	.67	10.69	.19	3.00	.7	24.7
12-12	4.02	.251	143.3	32.0	.60	9.61	.19	3.04	1.0	35.3
12-19	4.97	.310	178.5	12.0	1.57	25.15	.19	3.04	1.0	35.3
12-26	3.70	.231	135.4	none	n/a	n/a	n/a	n/a	n/a	n/a
1-2	4.76	.297	165.5	n/a	n/a	n/a	.17	2.72	.7	24.7
1-9	1.58	.099	53.8	none	none	none	.47	7.53	2.4	84.8
1-16	5.63	.351	191.2	none	none	none	.13	2.08	.7	24.7
1-23	6.02	.378	205.0	19.0	.85	13.62	.16	2.56	.82	29.0
1-30	6.39	.399	209.0	10.5	1.56	24.99	.16	2.56	.85	30.0
2-6	6.43	.401	219.0	26.0	.63	10.09	.16	2.56	.84	29.6
2-13	6.40	.400	220.0	23.0	.77	12.33	.18	2.88	.91	32.1
2-20	5.49	.343	189.0	22.5	.94	15.06	.21	3.36	1.09	38.5
2-27	3.87	.242	135.0	35.0	.76	12.17	.26	4.17	1.37	48.4
3-6	6.21	388	217.0	17.0	.96	15.38	.16	2.56	.83	29.3
3-13	6.07	.380	221.7	20.0	.84	13.46	.17	2.72	.83	29.3
3-20	5.65	.350	232.7	13.4	1.27	20.34	.17	2.72	.85	30.0
3-27	6.05	.380	219.5	27.0	.786	12.59	.21	3.36	1.06	37.4
4-3	4.49	.280	240.0	32.0	.83	13.30	.26	4.16	1.35	47.7
4-10	6.11	.380	217.4	16.0	1.26	20.18	.20	3.20	1.59	56.2
4-17	6.21	.390	200.7	18.0	1.14	18.26	.20	3.20	1.51	53.3
4-24	6.15	.380	202.7	24.0	.94	15.06	.23	3.68	1.09	34.5
5-1	6.07	.380	209.7	20.0	1.01	16.18	.20	3.20	1.03	36.4
5-8	6.37	.400	171.5	38.0	.49	7.85	.19	3.04	1.44	35.3
5-15	6.64	.410	205.2	34.0	.58	9.29	.20	3.20	1.13	39.9
5-22	4.82	.300		35.0	.76	12.18	.26	4.16		

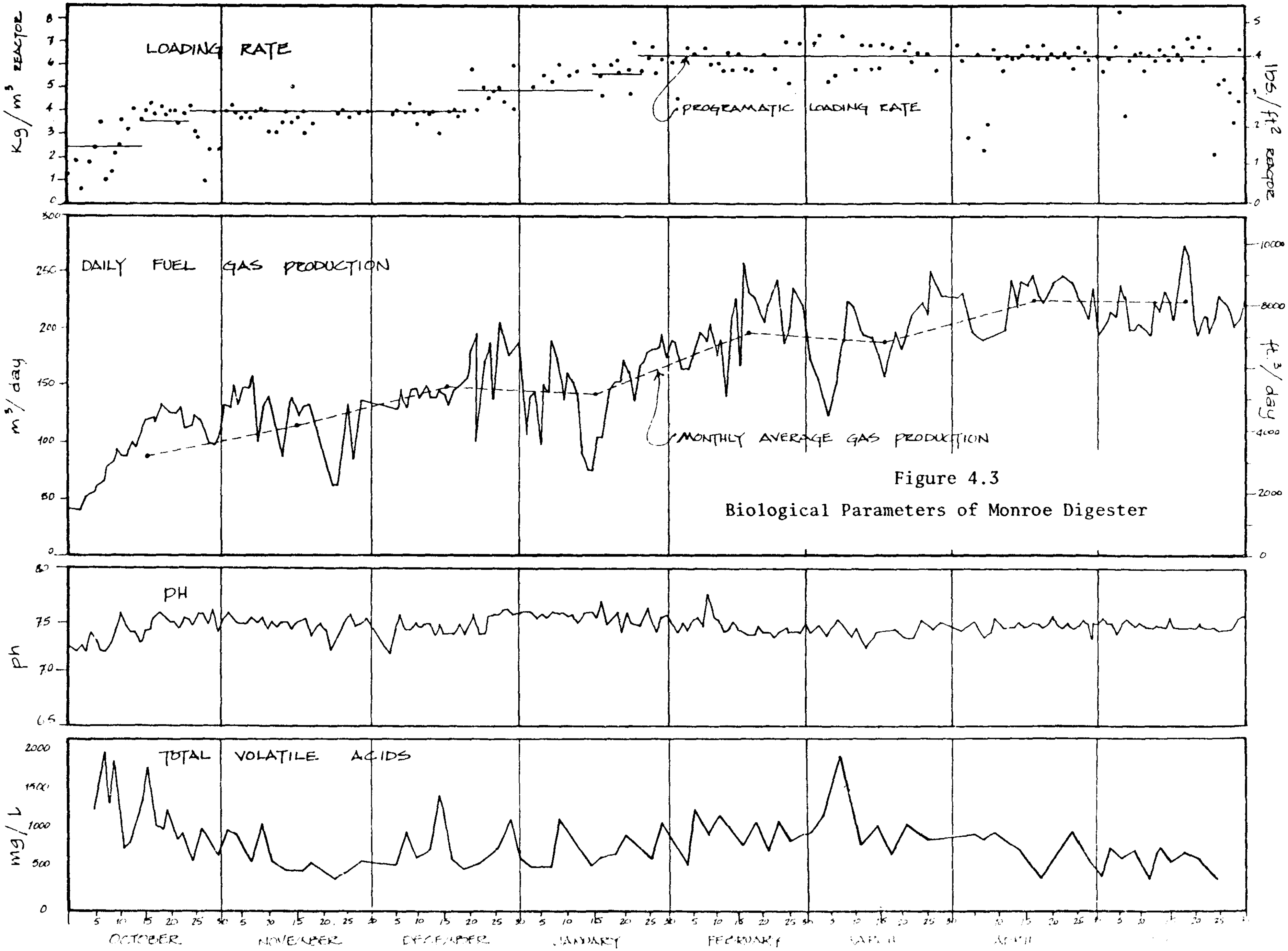


Figure 4.3

Biological Parameters of Monroe Digester over the year from an average of .44 m^3/kg destroyed in October to 1.04 m^3/kg destroyed in April. This may be due more to a stabilization of the bacteria population than to the decreased retention time. However, the overall result has been a steady increase in the gas produced per volatile solids added from .175 m^3/kgVS added to .23m^3/kgVS destroyed.

The biological parameters of the system have been remarkably stable (Figure 4.3). Over the year, p H has varied between 7.2 and 7.6, mostly staying in the range of 7.4 to 7.6. The system is very well buffered with an alkalinity of greater than 10,000 mg/liter throughout most of the year.

The total volatile acids are usually between 500-1000 mg/liter. However, the total volatile acids have risen when the digester has been loaded after a few days of no load. The largest rise (1800 mg/liter) occurred when such a situation was followed by a period of wide temperature fluctuations. However, the system rapidly recovered.

Since the digester operates as part of a working dairy farm, it is subject to all the uncertainties of the farming operation. The digester has operated during freezes, a flood, periods of overloading, underloading, no loading, and wide temperature fluctuations -- and has not shown any serious signs of biological stress. Dairy cow manure appears to be a very benign and stable substrate.

5.0 ENERGY PRODUCTION AND NET ENERGY

5.1 Overview

As an energy-producing technology, anaerobic digestion produces a steady supply of combustible fuel gas at 60-70% of the heat value of natural gas.

5.1.1 Energy Output. The energy output of the system can be in the form of gas which is produced by the process and can be burned directly for process heat. This requires a use for the gas in the proximity of the digester. An alternative is to burn the gas in an internal combustion engine and generate electricity which can be used on site or returned to the utility grid.

5.1.2 Energy Costs. There are also energy costs incurred by the system. These costs are principally energy required to heat and maintain the digester tank at 35°C, a temperature differential of up to 40°C (70°F) with the ambient temperature. This requires that a substantial amount of the gas produced be expended to heat the digester. Further energy costs are associated with pumping and mixing the manure. These demands are for electrical energy. If gas is the primary energy production, then these energy needs become an economic cost of the system as the energy is purchased from the local utility. If electricity is the principal output, then these are energy costs which reduce the net output.

A by-product of electrical energy production is waste heat from the engine. This can be used to heat the digester and negate the need for a boiler. The engine/generator are up to 20% efficient for electrical production. This additional use of waste heat improves overall efficiency to about 75% during peak heat demands in December.

5.1.3 Monitoring. In order to make a thorough energy analysis of the facility at Monroe, gas and electric meters were installed on key components of the system. Total gas production as well as gas consumption of the boiler and the engine/generator were monitored. Electric meters were installed to record the electricity used by the gas recirculation blower and by the pumps and lab. Another meter was used to record the electricity production of the I-C engine.

5.2 Gas Production

Gas Production has risen steadily since digester loading began in October 1977. Average gas production for May and June was 226.4 m^3(8000 ft^3) per day at 30% CO_2. This is equivalent to one cubic meter (35.2 ft^3) per cattle unit. This production rate is expected to continue as long as the herd size is kept constant. The gas production is equivalent to 83 x 10 m^3 (2.92 x $10^9 ft^3$) per year or 1,880.9 GigaJoules (1,781.2 mmBTU). Table 5.1 lists the energy production and consumption at the Monroe facility from November 1977 through May 1978. Since this was essentially a shakedown period for the system, the data cannot be considered to represent the optimum. However, it does indicate the potential for the system in terms of both increased gas production and decreased energy needs. Figure 5.1 shows the portion of the energy produced which was used for various functions (a straight kWh to MJoules conversion was used. No correction was made for conversion efficiencies.)

5.3 Electrical Energy Production. During December and January 1977-78, gas was also used to produce electricity in an internal combustion engine with a 40 kW (peak) generator. Engine cooling water was circulated through the internal heat exchanger. While the engine was running there was no need to run the boiler. The waste heat from the engine was sufficient to meet all the heating demands of the digester. Since the engine/generator set only provides electricity for the pumps, blower and the lab, it ran at far below its full electrical load. With all the electrical equipment on the site operating, the maximum draw was only 35 - 40 amps. The generator capacity is 83 amps. Consequently, the engine and generator performed at less than their maximum efficiency of 23% and 90% respectively. Rather than an overall efficiency of 20%, the engine/generator operated at an average efficiency of only 11% for electric production (Table 3.2,pg. 30).

Table 5.1

Energy Production and Consumption at Monroe Facility
November 1977 - May 1978

	total skin loss		influent heat		total heat demand		boiler consumption		boiler efficiency	total production		net energy	
	GigaJoules	mmBTU	GJ	mmBTU	GJ	mmBTU	GJ	mmBTU	%	GJ	mmBTU	GJ	mmBTU
month													
N	5.61	5.29	30.29	28.68	27.51* 35.87	26.05* 33.97	38.41	36.37	72	72.34	68.5	22.51	21.32
D	5.90	5.57	38.92	36.866	26.02* 44.81	24.64* 42.43	33.96	32.16	77	103.35	97.87	45.17	42.77
J	6.56	6.19	38.09	36.07	31.67* 44.63	29.99* 42.26	37.65	35.65	84	102.88	97.42	44.98	42.54
F	4.85	4.58	38.92	36.86	43.76	41.44	51.84	49.09	84	118.05	111.79	72.55	68.7
M	5.54	5.23	47.06	44.56	52.61	49.82	62.52	59.2	84	135.83	128.63	73.32	69.43
A	4.67	4.41	44.20	41.86	48.86	46.27	60.85	57.62	80	147.69	139.86	86.85	82.24
M	4.52	4.27	42.13	39.9	46.64	44.17	63.11	59.76	74	155.78	147.52	92.67	87.76

**Total heat demand for those days when the I-C engine was not providing digester heating*

month	mixing energy kWh	pumping energy kWh
N	(5287)	600
D	5194	620
J	5732	620
F	4700	560
M	2902	620
A	1988	600
M	1285	620

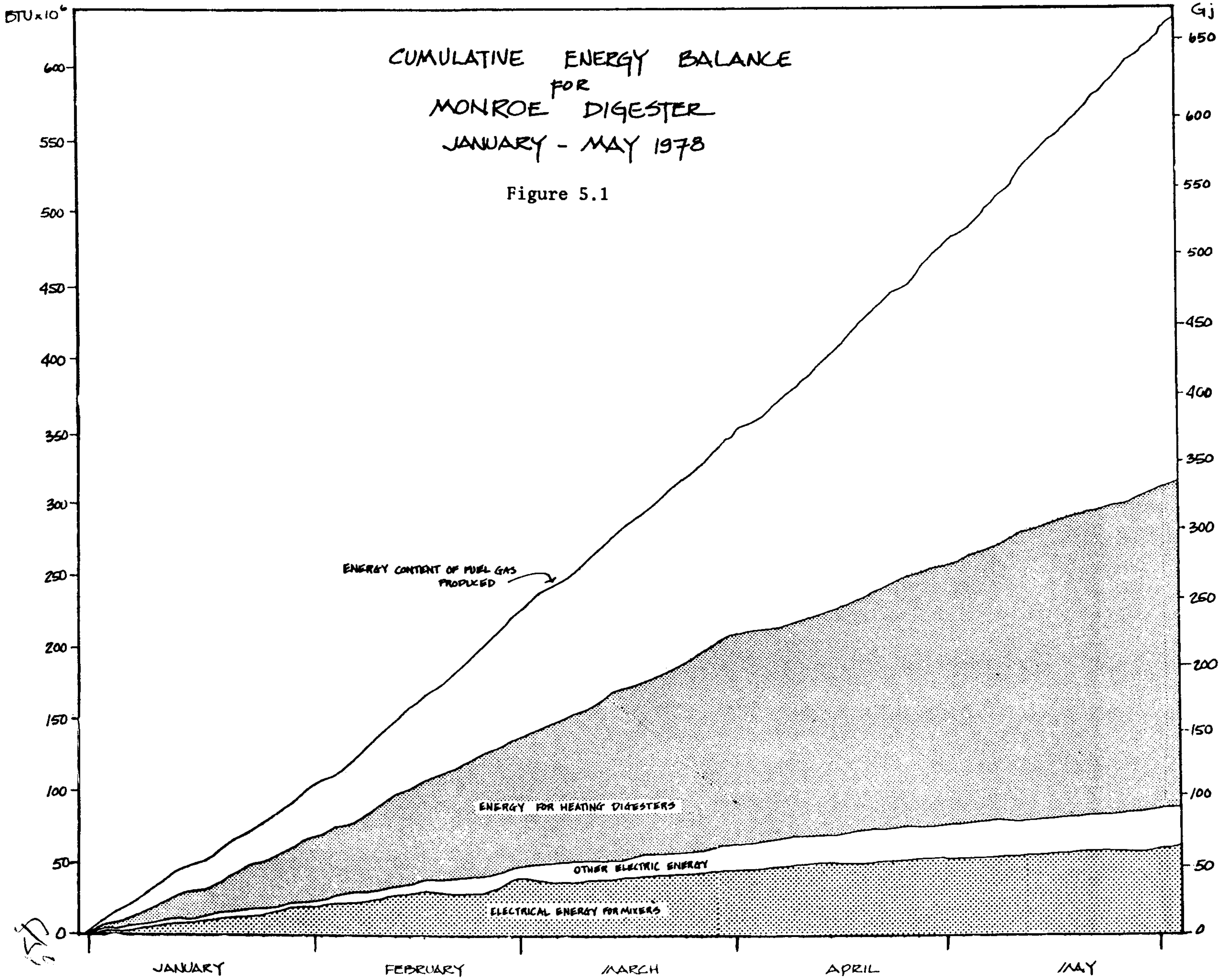

CUMULATIVE ENERGY BALANCE
FOR
MONROE DIGESTER
JANUARY - MAY 1978
BTU x 10^6
Gj
ENERGY CONTENT OF FUEL GAS PRODUCED
ENERGY FOR HEATING DIGESTERS
OTHER ELECTRIC ENERGY
ELECTRICAL ENERGY FOR MIXERS
JANUARY
FEBRUARY
MARCH
APRIL
MAY

Figure 5.1

When the heat energy recovery for digester heating is considered, however, the efficiency of the operation increases considerably. In both December and January, the electrical conversion efficiency averaged 11%. However, taking into account the heating demand which was met, the efficiency rose to 74% in December and 86% in January (Table 5.2). These high efficiencies are of course due to the fact that the engine generator was run during the coldest months of the year.

Table 5.2

Electrical Conversion Efficiency and Heating Demand
December 1977 - January 1978

	gas consumption		kWh produced	efficiency of elect. conversion	heating demand met		overall efficiency
	megaJ	BTU x 10^3			megaJ	mmBTU	
December	29.90	28.31	919	11%	18.79	17.79	74%
Janaury	17.17	16.26	519	11%	12.96	12.27	86%

In addition, the engine/generator was not used continuously throughout the day, so a large percentage of the waste heat could be utilized. If it were run continuously, more heat than was needed would be produced. Table 5.3 lists the maximum efficiencies possible if all the gas produced were used to generate electricity and all the digester heating was provided by waste heat.

The most ideal utilization of an engine/generator would be to run it only a few hours a day at full load and use the waste heat for influent heating. The electricity could be generated during peak load times and sold to a utility. This would integrate well with a farming operation which had a constant on-site gas consumption which was less than the total gas production. That portion which was excess could be used to generate electricity during peak loads to sell to a utility and waste heat could be used to heat influent. This would eliminate seasonal variation in gas availability since both consumption and production would be constant thoughout the year. Only the amount of waste heat which could be utilized would vary.

Table 5.3

Maximum Efficiency Possibilities
for Electrical Conversion of Gas Produced

	gas produced		electricity produced	heating demand		overall
	GigaJoules	*mmBTU*	kWh	GigaJoules	*mmBTU*	efficiency
month			x 10^3			%
J	162.4	*153.8*	9	85.6	*81.1*	73
F	146.7	*138.9*	8.1	70.5	*66.8*	68
M	162.4	*153.8*	9	74.4	*70.5*	66
A	157.1	*148.8*	8.7	64.5	*61.1*	61
M	162.4	*153.8*	9	58.2	*55.1*	56
J	157	*148.8*	8.7	49.3	*46.7*	53
J	162.4	*153.8*	9	44.9	*42.6*	48
A	162.4	*153.8*	9	45.6	*43.2*	48
S	157	*148.8*	8.7	50.5	*47.9*	52
O	162.4	*153.8*	9	62.8	*59.5*	59
N	157	*148.8*	8.7	72.2	*68.4*	66
D	162.4	*153.8*	9	80.9	*76.8*	70

conversion efficiency = 20%

5.4 Digester Heating

The two sources of heat loss from the digester are conductive losses through the skin and the displacement of warm effluent by the cold influent.

5.4.1 Skin Heat Losses.

The amount of heat lost through the skin is determined by the heat transfer coefficient of the reactor surface, its surface area and the temperature difference between the digester contents and the outside air. If the tank were uninsulated, the heat loss rate would be about 1.7 megaJoules/hr-°C (3000 BTU/hr-°F). The tank has 3½" of sprayed polyurethane foam on the interior of the roof, 4" of Dow Styrofoam SM_{tm} on the exterior walls, and sits on a one-foot thick uninsulated concrete slab. The heat loss rate of this insulated tank is 81.5 kiloJoules/hr-°C

(139 BTU/hr-°F) or 4% that of an uninsulated tank. The skin losses of our digester have varied from .2 GigaJoules (19mmBTU) per day in January to .14 GigaJoules (.13mmBTU) per day in May, with an average loss of .17 GigaJoules (.16mmBTU) per day. (Table 5.4)

5.4.2 Influent/Effluent Heat Losses. Influent heating is by far the dominant factor in digester heating demand and accounts for about 90% of the energy need in the system. The amount of heat necessary to raise the influent to 35°C is dependent on the volume, the percent solids and the original temperature. Following the procedure outlined in Marks (1967), the influent heat demand is:

$$Q = 62.4\ V_i\ (1\text{-}TS)$$

where: Q = heat quantity (BTU)
V_i= volume of influent (ft^3)
TS= ratio of total solids volume to total volume

Consequently, the heat needed for influent heating is inversely proportional to the percent solids and the retention time. At our present loading schedule with a 12-day retention time and 10% solids, influent heating requires 1.8 GigaJoules (1.7mmBTU) per day in January and .9 GigaJoules (.89mmBTU) per day in July. (Table 5.4)

5.4.3 Heat Exchanger. An awareness of the significance of the influent heating problem led to the design and installation of a counterflow influent/effluent heat exchanger. The heat exchanger was designed to operate at 40% efficiency. Tables 5.4, 5.5, 5.6, and 5.7 show the impact of a heat exchanger in the net energy situation of various sized digester systems. All of these systems are in the mesophilic range. Heat exchange is even more significant at thermophilic temperatures. Without influent/effluent heat exchange, a 60°C thermophilic digester operating at a five-day retention time must produce six volumes of gas per volume of reactor to get the same net yield as a mesophilic digester operating at 35°C with a ten-day retention time producing 1.5 volumes of gas per volume of reactor.

5.4.4 Boiler. The National 209 Series gas boiler which is used to heat the digester has a rated efficiency of 80%. Over the past eight months, it has averaged 77% efficiency. Heating the digester accounted for 69% of the total gas production in November and 41% in April and May (Figure 5.1).

An effectively operating heat exchanger could have lowered these percentages to 41% in November and 24% in May.

5.5 Electrical Energy Requirements, Mixing and Pumping

5.5.1 Pumping and Influent Mixing. Electrical energy is consumed to mix and load manure. The pumping vaies between 20 and 40 kWh/day, depending on the amount of influent mixing needed. This varies with the ambient temperatures and the percent solids of the slurry.

5.5.2 Digester Mixing. In municipal sewage treatment, the mixing requirements are substantially greater than the relatively homogeneous dairy manure substrate demands. The energy used for mixing the digester contents at Monroe has been significantly reduced over the year. The mixer blower ran continuously during the first five months of operation. Electrical consumption during that time was over 180 kWh/day, which was approximately 90% of the total electric energy used. The blower began to run on a timed cycle in February. Mixing was reduced to ten minutes on and ten minutes off, then to ten minutes on and 20 minutes off, and finally to 10 minutes on and 50 minutes off. Electrical consumption is now 30 kWh/day for mixing.

This represents a substantial improvement in the net energy and economic performance of the system. If the energy production is gas, then the electric energy used represents a substantial cost which increases the "cost" of the gas produced. In a lifecycle analysis, this cost is escalated at a rate substantially above the overall inflation rate. Thus, its impact on the long term economic feasibility is even more substantial.

If the energy production is electricity, the mixing energy becomes an energy cost and reduces the total output of the system. Since the economics of electricity production are difficult, a large reduction due to mixing requirements substantially reduces the feasibility of this option.

5.6 Net Energy Production

The following four tables represent the year-round net energy production for various sized dairies. All systems are rigid tanks similar to that at Monroe and all operating characteristics are based on the working experience of the Monroe system with the exception of a 20% electrical conversion efficiency which is the rated efficiency for the Waukesha engine/Kato generator set when operating at full load.

Gas production is based on a one cubic meter (35 ft^2) per cattle unit per day with a methane content of 60%. Operating temperature is 35°C. Weather Bureau data showing average monthly temperatures at Monroe were used for ambient. The heat loss rate for the digester is assumed to be 111.4 kJ/hr-°C. Digester sizes for the Monroe facility (Table 5.4) and the 200 cow-dairy (Table 5.6) are the same 25' diameter, 13.5' high tanks now at Monroe. The 400-cow dairy (Table 5.7) system is two such tanks and the 100-cow dairy (Table 5.5) is a 10'x10' tank. Retention times are 10 days on all systems, with the exception of the Monroe facility where the actual retention time is 12 days. All loading is at 10% solids. Influent temperature is assumed to be ambient. Boiler efficiency is assumed to be 75%; heat exchange efficiency, 40%; and electric conversion efficiency, 20%. Net gas production is listed both with and without heat exchanger. Net electrical production assumes all gas produced will be used to produce electricity and will meet the electric demands of the site. Electric requirements are for pumps and gas recirculation mixing. Mixing energy demands are at the present rate of ten minutes per hour mixing. This may prove to be more than necessary.

Table 5.4

Energy Production - Monroe Facility
(180 cows)

	gas production		heat required with heat exchanger		heat required without heat exchanger		net gas with heat exchanger		net gas without heat exchanger		electricity		
	GJ	*mmBTU*									produced	required	net
												kWh x 1000	
J	162.4	*153.8*	56.0	*53.0*	85.04	*81.1*	106.3	*100.7*	77.0	*72.7*	9.0	1.6	7.4
F	146.7	*138.9*	46.1	*43.7*	70.5	*66.8*	100.5	*95.2*	76.1	*72.1*	8.1	1.5	6.6
M	162.4	*153.8*	48.7	*46.1*	74.4	*70.5*	113.6	*107.6*	87.9	*83.2*	9.0	1.6	7.4
A	157	*148.8*	42.2	*40.0*	64.5	*61.1*	114.9	*108.8*	92.7	*87.7*	8.7	1.6	7.1
M	162.4	*153.8*	38.0	*36.0*	58.2	*55.1*	124.3	*117.7*	104.2	*98.7*	9.0	1.6	7.4
J	157	*148.8*	32.2	*30.5*	49.3	*46.7*	124.9	*118.3*	107.8	*102.1*	8.7	1.6	7.1
J	162.4	*153.8*	29.5	*27.9*	44.9	*42.6*	133	*125.9*	119.4	*113.1*	9.0	1.6	7.4
A	162.4	*153.8*	29.8	*28.2*	45.6	*43.2*	132.5	*125.5*	116.8	*110.6*	9.0	1.6	7.4
S	157	*148.8*	33.1	*31.3*	50.5	*47.9*	124	*117.5*	106.6	*100.9*	8.7	1.6	7.1
O	162.4	*153.8*	41.1	*38.9*	62.8	*59.5*	121.2	*114.8*	99.5	*94.2*	9.0	1.6	7.4
N	157	*148.8*	47.3	*44.8*	72.2	*68.4*	109.8	*104.*	84.9	*80.4*	8.7	1.6	7.1
D	162.4	*153.8*	52.9	*50.1*	80.9	*76.6*	109.5	*103.7*	81.5	*77.2*	9.0	1.6	7.4

digester temperature = 35°C

boiler efficiency = 75%

electrical conversion efficiency = 20%

heat exchange efficiency = 40%

electrical demand = 52 kWh/day

Table 5.5

Energy Profile for 100-Cow Dairy

	gas production		heat required with heat exchanger		heat required without heat exchanger		net gas with heat exchanger		net gas without heat exchanger		electricity (kWh x 1000)		
	GJ	mmBTU									produced	required	net
J	88.39	*83.7*	35.38	*33.5*	53.96	*51.1*	52.91	*50.1*	34.43	*32.6*	4.9	1.0	3.9
F	79.83	*75.6*	29.15	*27.6*	44.35	*42.0*	50.58	*47.9*	35.48	*33.6*	4.4	.9	3.5
M	88.39	*83.7*	30.84	*29.2*	46.99	*44.5*	57.45	*54.4*	41.40	*39.2*	4.9	1.0	3.9
A	85.54	*81.00*	26.72	*25.3*	40.66	*38.5*	58.82	*55.7*	44.88	*42.5*	4.7	.9	3.5
M	88.39	*83.7*	24.08	*22.8*	36.64	*34.7*	64.31	*60.9*	51.74	*49.0*	4.9	1.0	3.9
J	85.54	*81.00*	20.38	*19.3*	31.05	*29.4*	65.16	*61.7*	54.49	*51.6*	4.7	.9	3.5
J	88.39	*83.7*	18.59	*17.6*	28.41	*26.9*	69.70	*66.0*	59.98	*56.8*	4.9	1.0	3.9
A	88.39	*83.7*	18.80	*17.8*	28.72	*27.2*	69.48	*65.8*	59.66	*56.5*	4.9	1.0	3.9
S	85.54	*81.00*	20.91	*19.8*	32.00	*30.3*	64.63	*61.82*	53.54	*50.7*	4.7	.9	3.5
O	88.39	*83.7*	26.08	*24.7*	39.60	*37.5*	62.30	*59.0*	48.79	*46.2*	4.9	1.0	3.9
N	85.54	*81.00*	29.88	*28.3*	45.41	*430*	55.55	*52.6*	40.13	*38.0*	4.7	.9	3.5
D	88.39	*83.7*	33.48	*31.7*	51.00	*48.3*	54.91	*52.0*	37.38	*35.4*	4.9	1.0	3.9

Digester temperature = 35°C

Boiler efficiency = 75%

Electric conversion efficiency = 20%

Heat exchange efficiency = 40%

Electrical demand = 52 kWh/day

Table 5.6

Energy Profile for a 200-Cow Dairy

	gas production		heat required with heat exchanger		heat required without heat exchanger		net gas with heat exchanger		net gas without heat exchanger		electricity produced	electricity required	electricity net
	GJ	*mmBTU*									(kWh x 1000)		
J	176.8	*167.4*	64.9	*61.5*	100.5	*95.2*	111.8	*105.9*	76.2	*72.2*	9.8	1.7	8.1
F	159.7	*151.2*	53.5	*50.7*	82.8	*78.4*	106.1	*100.5*	76.9	*72.8*	8.9	1.5	7.4
M	176.8	*167.4*	56.5	*53.5*	87.5	*82.9*	120.2	*113.8*	89.2	*84.5*	9.8	1.7	8.1
A	171.1	*162*	49.0	*46.4*	75.8	*71.8*	122.1	*115.6*	95.3	*90.2*	9.5	1.6	7.9
M	176.8	*167.4*	44.1	*41.8*	68.3	*64.7*	132.6	*125.6*	108.5	*102.7*	9.8	1.7	8.1
J	171.1	*162*	37.4	*35.4*	57.3	*54.3*	133.7	*126.6*	113.2	*107.2*	9.5	1.6	7.9
J	176.8	*167.4*	34.1	*32.3*	52.9	*50.1*	142.7	*135.1*	123.9	*117.3*	9.8	1.7	8.1
A	176.8	*167.4*	24.6	*32.8*	53.5	*50.7*	142.1	*134.6*	123.2	*116.7*	9.8	1.7	8.1
S	171.1	*162*	38.3	*36.3*	59.3	*56.2*	132.7	*125.7*	111.7	*105.8*	9.5	1.6	7.9
O	176.8	*167.4*	47.7	*45.2*	73.8	*69.9*	129.0	*122.2*	103.3	*97.5*	9.8	1.7	8.1
N	171.1	*162*	54.8	*51.9*	84.9	*80.4*	116.3	*110.1*	86.2	*81.6*	9.5	1.6	7.9
D	176.8	*167.4*	61.4	*58.1*	95.0	*90.0*	115.4	*109.3*	81.7	*77.4*	9.8	1.7	8.1

Digester temperature = 35°C

Boiler efficiency = 75%

Electrical conversion efficiency = 20%

Heat exchange efficiency = 40%

Electrical demand = 55 kWh/day (mix and pump)

Table 5.7

Energy Profile for 400-Cow Dairy

	gas production		heat required with heat exchanger		heat required without heat exchanger		net gas with heat exchanger		net gas without heat exchanger		electricity		
	GJ	*mmBTU*									produced	required (kWh x 1000)	net
J	353.5	*334.8*	129.7	*122.8*	200.9	*190.2*	223.9	*212.0*	152.7	*144.6*	19.6	2.5	17.1
F	319.3	*302.4*	106.9	*101.2*	165.5	*156.7*	212.5	*201.2*	153.9	*145.7*	17.7	2.3	15.4
M	353.3	*334.8*	112.9	*106.9*	174.9	*165.6*	240.6	*227.8*	178.7	*169.2*	19.6	2.5	17.1
A	342.1	*324.0*	97.8	*92.6*	151.4	*143.4*	244.3	*231.3*	190.7	*180.6*	19.0	2.4	16.6
M	353.3	*334.8*	88.1	*83.4*	136.4	*129.2*	264.4	*251.4*	217.1	*205.6*	19.6	2.5	17.1
J	342.1	*324.0*	74.7	*70.7*	115.5	*109.4*	267.5	*253.3*	226.5	*214.5*	19.0	2.4	16.6
J	353.3	*334.8*	68.1	*64.5*	105.6	*100.*	285.3	*270.2*	247.9	*234.8*	19.6	2.5	17.1
A	353.5	*334.8*	68.1	*65.4*	105.6	*101.3*	285.3	*269.3*	247.9	*233.5*	19.6	2.5	17.1
S	342.1	*324.*	76.9	*72.8*	118.6	*112.3*	265.5	*251.4*	223.6	*211.7*	19.0	2.4	16.6
O	353.5	*334.8*	95.3	*90.7*	147.4	*139.6*	258.3	*244.6*	206.0	*195.1*	19.6	2.5	17.1
N	342.1	*324.*	109.5	*103.7*	169.5	*160.5*	232.6	*220.3*	172.6	*163.4*	19.0	2.4	16.6
D	353.5	*334.8*	122.6	*116.1*	189.7	*179.6*	230.9	*218.7*	163.8	*155.1*	19.6	2.5	17.1

Digester temperature = 35°C

Boiler efficiency = 75%

Electric conversion efficiency = 20%

Heat exchager efficiency = 40%

Electric demand = 82 kWh/day (mix & pump)

6.0 ECONOMICS OF ANAEROBIC DIGESTION

6.1 Economics of Consumer Energy Production

The economics of the Monroe digester facility are beset with the same uncertainties as any economic analysis associated with an essentially consumer technology which has a multiplicity of tangible and intangible benefits to its owner, but which also produces energy. The current literature on these solar-based technologies has for the most part ignored these consumer benefits in favor of evaluating the economic costs and benefits associate with the energy. This perspective is at best conservative since any proper cost-benefit analysis should attempt to quantify all the costs and all the benefits.

It is, however, difficult if not impossible to choose *a priori* those benefits which a given farmer will accrue as a result of an investment in these technologies (e.g., odor reduction, water pollution control, integrated manure handling, self-sufficiency, etc.). To one farmer, these end benefits could be essential for continued operation; to another in a more remote region, pleasant amenities.

A second short coming of long term analysis of technology which produces (or saves) energy for a consumer is the assessment of the future cost of the alternative, namely fossil fuels and electricity, available from the larger economy. It is reasonable to predict a rising energy cost. However, the size of this escalation and the relative impact of inflation will have a decisive impact on the outcome of the analysis. The analysis then becomes a view of the future which may or may not reflect reality.

If a utility were to make a comparable investment, these costs could be easily quantified in the context of a rate of return (set by the public utilities commission) on a given capitalization. For the farmer, this has less relevance and properly the analysis should vary accordingly.

6.2 Economic Evaluation Technique

For purposes of this evaluation, the economics were approached two ways:

6.2.1 A "Cost of Energy" Analysis. This analysis focused on the capital costs, operating costs, depreciation, tax benefits, interest rates and inflation, balanced against energy production over the life of the facility. The results of this analysis in a dollars per million BTU produced. This reflects the cost of delivering the energy absent other benefits of the system.

To date, we have not been able to quantify or observe any other benefit of this process at the Monroe facility since the digester is operated completely outside the Farm operation. Furthermore, since the Farm is under no immediate pressure to upgrade its manure handling facilities or its water quality control procedures, performing a site-specific comparative economic evaluation is not possible.

6.2.2 A "Rate of Return" Analysis. This analysis evaluates energy generated by the plant in the context of fuel cost escalation and inflation. This gives a dollar value to the energy produced over the life of the plant from which an average rate of return on investment is calculated. With the exception of fuel cost escalation, the assumptions here are identical to the Cost of Energy analysis.

It should be noted that this Rate of Return analysis includes interest costs or capital opportunity costs as a portion of the "investment capital." This produces a relatively conservative analysis which, in effect, is the "rate of return" above the opportunity cost of the invested capital. Thus, if a rate of return is 2% and the capital cost if 9%, the total rate of return on the installed capital cost only is 11%. If a farmer were to outlay all the capital to install the system at the outset, the latter figure would be a more accurate rate of return estimate.

6.3 Capital Costs

6.3.1 Capital Costs of Monroe Digester. The capital costs of the Monroe system as built are summarized in Table 6.1.

6.3.1.1 Modified tank requirements. It is important to understand that this system is a prototype system. The design decisions were in large part based on scanty data and inadequate comprehension of the parameters of digestion for dairy cow manure. Most of the understandings and data necessary to this design process have been developed during the last nine months of operating experience. The system as built was overdesigned given the shorter retention

Table 6.1

Capital Costs of the Monroe Digester

Tanks	
Digester & installation	$18,000
Influent/effluent	3,400
Storage tanks	3,000
Manure handling	
Pumps	6,400
Pipes & plumbing	8,500
Heat exchanger (influent/effluent)	2,200
Gas Handling	
Boiler	1,500
Draft tube-heat exchanger	2,500
Blower mixer	3,300
Compressor	3,200
Safety & control	5,700
Other	
Electrical	3,000
Engine/generator	7,000
Auxiliary building & miscellaneous	2,500
Labor[1]	
Farm labor (in-kind)	5,000
Ecotope personnel	10,000
Total Construction	$85,200
Engineering & feasibility	11,000
Project management (Ecotope)	22,800
	$119,000[2]

[1]Labor includes only that labor not included in sub-contractor costs to install the machinery and components. This is farm cadre and inmate labor and direct Ecotope labor involved in constructing the facility.

[2]Additional expenses such as the creamery boiler, flood damage, publication of feasibility study, unusual site preparation and drainage are not included in this final total

time at which the digester is operated. The limits on the system have become the amount of manure available rather than any limit of machinery. At current levels, only one of the reactor tanks can be used. Obviously, if the system were properly sized, the tank capacity would be reduced substantially (see Section 3.1).

6.3.1.2 Modified pumping and plumbing requirements. Secondly, the pumping requirements of this higher solids loading and substrate are different from those in the original design specifications. With higher solids, a greater amount of horsepower is required for preparing the influent. A progressive cavity pump and flexible pumping is probably required to achieve proper heat exchange. The I-C engine is required to produce electricity; however, if this is the primary output, then the boiler, heat exchanger and continuous loading features would be supplanted by the waste heat from the engine. Conversely, if the system is to produce gas as its principal energy output, the I-C engine is unnecessary.

6.3.2 Costs for Optimized Systems. Table 6.2 reflects capital cost estimates based on these features under three design conditions:

(1) A 130-cattle unit (100 cows) dairy.

(2) A 260-cattle unit (200 cows) capacity comparable to the current Honor Farm operation.

(3) A 520-cattle unit (400 cows) dairy, comparable to the actual capacity of the Monroe system as designed.

Each design condition is then modified for electricity as the primary production and gas as the primary energy production.

Labor is included as a separate item and estimated from our Monroe experience. Since some of the labor was done by inmates, the labor cost of the Monroe digester is less than completely accurate. However, given skilled and experienced workers, undoubtedly these systems could be constructed within the labor budget of the Monroe facility. Engineering time has been discounted as the amount of development work required on the Monroe digester was far greater than would be required on a digester package which might be made available to a farmer.

Table 6.2

Comparative Capital Costs of Different Digester Scales

(in thousands of dollars)

	100 cows		200 cows		400 cows		Monroe
energy output:	gas	*elect.*	gas	*elect.*	gas	*elect.*	gas/elect.
Tanks	13.0	*11.0*	15.4	*12.4*	23.4	*20.4*	24.4
Manure handling	10.0	*7.0*	12.2	*8.5*	14.0	*10.0*	17.1
Gas handling	13.2	*15.0*	13.8	*15.5*	14.4	*16.0*	16.2
Other	4.5	*10.0*	5.0	*11.5*	5.5	*12.5*	12.5
Labor	12.0	*12.0*	14.0	*14.0*	16.0	*16.0*	15.0
Engineering & contractor profit, etc. (15%)	8.0	*8.2*	9.0	*9.3*	11.0	*11.2*	33.8
Total	60.7	*63.2*	69.4	*71.2*	84.3	*86.1*	119.0

6.4 Energy Production

The comparative energy output and the energy requirements of the Monroe digester and other optimized digesters are presented in Table 6.3 as adapted from Section 5.6, Net Energy. These reflect the actual operating conditions of the Monroe facility in the Western Washington climate. If the primary energy output of the system is gas, then digestion heat requirements reduce the net output of the system. The heat required is to bring the cold influent to 35°C and to replace heat lost through the digester skin to the outside environment. To provide this heat, gas is burned in a boiler at 75% efficiency.

The pumping and mixing energy requirements are an operating expense since the form of energy used, electricity, is not produced by the system.

Table 6.3

Comparative Energy Production
of Various Scale Systems

	mmBTU/year	*kWh/year (000)*
400 cow dairy:		
Gas Production		
With heat exchanger	2833.5	
Without heat exchanger	2258.8	
Electricity Production		*201.5*
200 cow dairy:		
Gas Production		
With heat exchanger	1424.6	
Without heat exchanger	1125.9	
Electricity Production		*95.7*
100 cow dairy:		
Gas Production		
With heat exchanger	687.3	
Without heat exchanger	532.3	
Electricity Production		*44.8*
Monroe facility (180 cow dairy):		
Gas Production		
With heat exchanger	1339.7	
Without heat exchanger	1092.9	
Electric Production		*86.8*

If the primary energy output of the system is electricitv, then the waste heat resulting from the inefficiencies of the conversion of gas to electricity is all that is required to heat the digester. The net output of electricity is reduced by the pumping and mixing motor requirements of the system.

6.5 Operating Costs

The operating cost of the plant reflect the experience of operating the plant as currently designed. If equipment were specified which was more nearly adapted to the system, less maintenance could be required. However, this figure allows for the overhaul of one major pump, motor or blower per year, plus miscellaneous maintenance items.

In addition, the cost of electric energy is included as an operating cost -- which applies only to a system which produces gas as its primary production. The cost of electricity is escalated in the analysis at the same rate as the fuel costs used to calculate the value of the gas output.

Operator time is included at one hour per day at a payment of $4.00 per hour. This expense may or may not be a normal part of a farming operation. The farmer could assume that time in her/his own operation of the farm. Thus, the analysis includes both options, with and without operator labor.

Table 6.4 presents the operation and maintenance costs associated with the relevant systems.

Table 6.4
Comparative Annual Operator and Maintenance Costs

	100 cows		200 cows		400 cows		Monroe
energy output:	gas	*elect.*	gas	*elect.*	gas	*elect.*	
Maintenance	$800	*$1000*	$1200	*$1400*	$1500	*$1700*	$1200
Electricity	166		250		390		240
Operator	1460	*1460*	1460	*1460*	1750	*1750*	2190
TOTAL							
W/ Operator	2526	*2460*	2910	*2860*	3640	*3450*	3780
W/ Operator out	966	*1000*	1450	*1400*	1890	*1700*	1590

6.6 Energy Cost and Rate of Return Analysis

6.6.1 Methodology. The cost of energy produced at a methane plant is summarized in Table 6.5 The procedures for computing the table are presented in Appendix A, with the relevant assumptions.

Table 6.5

Comparative Energy Costs and Rates of Return
Complete Mix Mesophilic Digesters
for Various Sized Dairy Farms

	Without Operator Cost		With Operator Cost	
	rate of return (%)	*energy cost/ unit produced* ($)	rate of return (%)	*energy cost/ unit produced* ($)
400 cow dairy:				
Gas Production (MBTU)				
With influent/effluent heat exchanger	7.4%	*$2.36*	7.1%	*$2.98*
With heat exchanger	6.4	*2.94*	6.0	*3.71*
Electricity Production (kWh)	1.9	*.028*	.9	*.037*
200 cow dairy:				
Gas Production				
With heat exchanger	5.1	*3.69*	4.4	*4.91*
Without heat exchanger	4.1	*4.56*	3.2	*6.21*
Electricity Production	*	*.050*	*	*.068*
100 cow dairy:				
Gas Production				
With heat exchanger	2.5	*6.04*	1.3	*8.17*
Without heat exchanger	1.4	*7.59*	*	*10.33*
Electricity Production	*	*.088*	*	*.120*
Monroe pilot plant (180 cows):				
Gas Production				
With heat exchanger	3.4	*4.89*	2.6	*6.52*
Without heat exchanger	2.5	*5.99*	1.4	*8.00*
Electricity Production	*	*.066*	*	*.092*

*Payback period exceeds life of the digester

This procedure uses standard lifecycle and present value procedures to arrive at adjusted long term energy costs and values. The analysis is designed to integrate features of a standardized utility energy cost and analysis (Siegal, *et al*, 1972) and a consumer lifecycle energy analysis (Straub, *et al*, 1976). The "cost of energy" methodology develops the cost per mmBTU of the energy produced by the technology. The "rate of return" methods show the return on investment of the total capital costs of the net benefit (the value of the energy produced less expenses of production.

6.6.2 System Configurations. The analysis is conducted on three distinct configurations for three plant sizes and the Monroe facility as built.

(1) Gas production as the primary energy output, with electric energy treated as an expense and with an influent/effluent heat exchanger operating at 40% efficiency, thus reducing the amount of gas required to maintain digester temperature.

(2) Gas production as the primary energy output without the benefit of an influent/effluent heat exchanger.

(3) Electricity as the primary energy output with conversion efficiencies of 20% and waste heat utilized to maintain digester temperature.

6.6.3 System Operations. The economics of each plant is further modified by the wages paid an operator included as an operation expense as opposed to a farmer operating as part of the farming operating. The analysis was conducted for both eventualities.

6.6.4 Economies of Scale. The rate of return for the digesters was over 7% for a large scale system. However, for smaller systems it falls below 3% per year. Obviously, this technology has substantial economies of scale associated with it. Figures 6.1 and 6.2 illustrate a classic increased costs curve per unit output.

Given a 25-year life, the energy costs of a gas producing installation have a break-even point between 250- to 360-cow dairies when compared with current gas prices. When compared with the future gas cost (1985) from "frontier" sources, the units become cost competitive for dairies as

ECONOMIES OF SCALE FOR RIGID TANK, COMPLETE MIX, MESOPHILIC DIGESTER

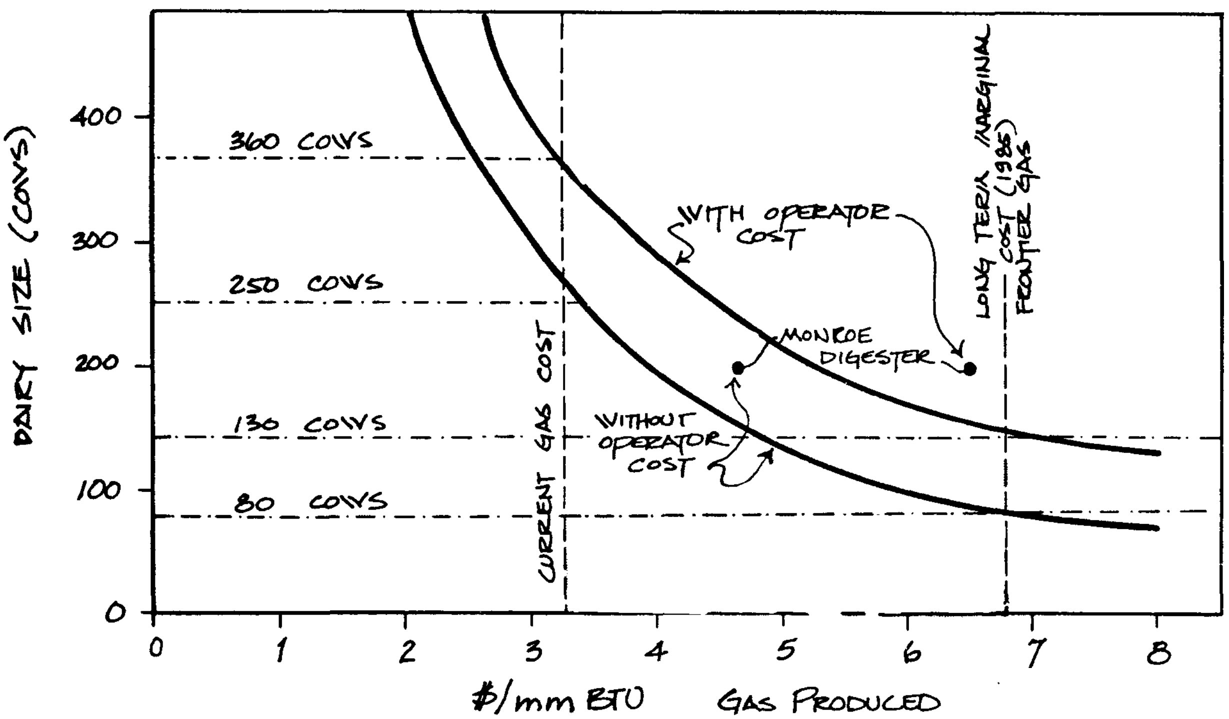


Figure 6.1

Declining Cost Curve - Gas Production

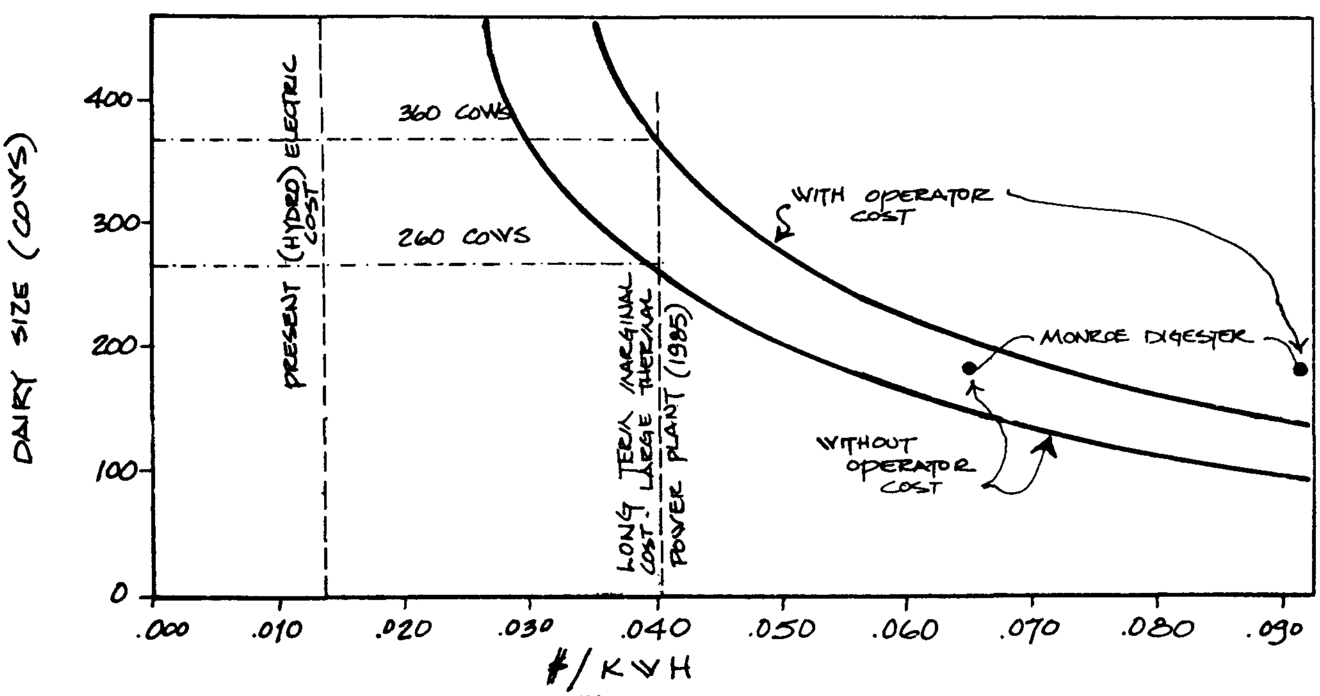


Figure 6.2

Declining Cost Curve - Electric Production small as 80-130 cows. It is likely, however, that small scale systems would not compete with alternative digester designs in this range, such as plug flow or batch digesters.

When the system is designed to produce electricity, the economic feasibility is substantially reduced. Under that condition, the rates of return fall below 2% per year, even in the most cost effective systems -- and in the small digester, the rate of return is negative (that is, the capital costs and capital opportunity costs are not recovered at escalating energy values over the 25-year life). This is in part due to the very low value for electricity in this region -- 13 mils/kWh. Since the minimum electricity cost is 28 mils for these digester technologies, electricity production appears very weak economically.

However, when compared to the marginal cost of electricity for this region (about 40 mils), the value of the investment becomes more clear. If the unit is to be competitive at the margin with other new sources of electricity (large thermal electric power plants), then systems for dairies of the scale of 260- to 360-cows appear competitive. Since the farmer is not a utility, it will be difficult for her/him to rationalize the investment without substantial subsidies. However, when given the long term marginal cost of electricity, this is probably justifiable. It should also be noted that the electricity costs that are at the "margin" in the Northwest region are already the current average cost in many other areas of the United States. The feasibility of the system in other regions would be greatly improved with this high cost of electricity as the competitor. Indeed, rates of return and energy costs for the medium scale dairies would be similar to direct gas production.

The economics of the Monroe digester itself are modified by the costs associated with a pilot facility. As a result, the costs fall somewhat above the cost curves set by the more optimized systems. The Monroe facility has sufficient capacity to handle as many as 400 cows and was outfitted for both gas production and gas handling in electric production. All of this capital cost is balanced against gas production from a plant operating at less than half capacity. The Monroe plant, however, does provide the basis for estimating both the costs and production of the other systems.

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APPENDIX A

Economic Formulas and Assumptions

1. Capital Cost

$$CC = C - CR \qquad \text{(Clean Water Act)}$$

$$AC = cc \left(\frac{i}{1 - (1+i)^{-N}} \right)$$

Total Capital Cost (present value)

$$TCC = AC \left(\frac{1 - (1+r)^{-N}}{ln(1+r)} \right)$$

2. Depreciation

$$DC = \left\{ CC \; (1+D)^{TR} \cdot \frac{1 - (1+r)^{-N}}{ln(1+r)} \right\} = \text{Depreciation}$$

3. Operating Costs, Total O.C.

$$OC = (M + L)N$$

4. Total Energy Costs (present value) (Production or Consumption)

$$TE = E\left\{ \frac{\left(\frac{1+e}{1+r}\right)^{N} - 1}{ln\left(\frac{1+e}{1+r}\right)} \right\} = EC$$

5. Rate of Return (present value)

$$(1+M) = \left(\frac{TE - OC - EC - DC}{TCC} \right)^{1/N}$$

6. Average Cost of Energy (present value)

$$CE = \frac{AC + OC + EC \quad DC}{EP \cdot N}$$

Where:

i = interest rate or opportunity cost on initial capital

r = inflation rate

e = fuel cost escalation

N = life of project

CO = total construction cost

CR = federal credits(Clean Water Act, 1977)

CC = capital cost

AC = annual capital cost with interest

TCC= total capital cost over project life

DC = depreciation tax credit

TR = tax rate

M = maintenance

L = operator labor

OC = operating cost

E = annual energy cost(present value)

TE = total energy value over project life

EC = total energy cost (plant operator)

R = rate of return

CE = value of energy produced

EP = total energy production (BTU, kWh, etc.)

Assumptions:

i = .09

r = .06

e = .15

N = 25 years

E = $3.10/MBTU gas
$2.96/MBTU oil
$.013/kWh electricity

20% tax bracket,

Straight-line depreciation at 4% per year

CR = $3500 "Clean Water Act" credit

O&M cost = 4% of expendible capital costs (pumps, blower, etc.) per year

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