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Final Report

# ENERGY INTEGRATED DAIRY FARM SYSTEM IN PUERTO RICO

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# ABSTRACT

As part of the U.S. Department of Energy's Energy Integrated Farm System (EIFS) program, principles of energy integrated farming were applied to the Río Cañas Dairy Farm, a privately-owned dairy farm in Puerto Rico. The Río Cañas Dairy Farm was one of the largest dairy farms in Puerto Rico with a milking herd of 400 cows. Objectives of the project were to (a) increase the farm's energy self-sufficiency, and (b) provide the farm with an environmentally-acceptable method of managing animal wastes.

The project consisted of three subsystems. As part of the Anaerobic Digestion and Electrical Production subsystem, animal wastes were fed to two anaerobic digesters where methane gas was produced by bacterial degradation of organic material. The methane gas fueled an engine-generator to produce electricity for farm use and for sale to the public utility. Under the Farm Waste Management subsystem, animal wastes were partially stabilized by bacterial action within the digesters, and the digester effluent passed to a liquid-solid separator. Solid fraction from the liquid-solid separator was composted and either used as bedding material for the cows or marketed as soil conditioner. The liquid fraction flowed to a storage pond. This liquid was used in the Greenfeed subsystem to fertilize forage crops for the cows.

Estimated energy savings of the system were 1,705 MBtu for the first two subsystems and 7,718 MBtu's for all three subsystems. Simple payback for the first two subsystems was very long (20 years) because (a) facilities for effective manure recovery did not exist on the farm at the outset of the project, (b) operational costs for manure collection were charged against the project, and (c) system components were oversized. Including the Greenfeed subsystem, simple payback for the project was 8.2 years. Assuming that manure collection facilities and practices already existed and assuming proper sizing of all components, simple payback for the Anaerobic Digestion and Electrical Production subsystem and the Farm Waste Management subsystem was 5.8 years. Using data from this project, an estimate of the return on investment was projected for different herd sizes. These analyses suggested that for dairy farms with less than 500 cows, anaerobic digester systems are only marginally profitable.

Successful implementation of this type of system involves several factors including (a) existing manure collection facilities and practices; (b) simplicity in the system design so that system operation is uncomplicated, requires a minimum amount of time, and requires a minimum amount of maintenance; (c) careful sizing of system components; and (d) willingness on the part of farm management to accept the additional management tasks involved.

# ACKNOWLEDGMENTS

Funding for this project was received from the U.S. Department of Energy (Contract No. DE-FC07-80CS40376), the Puerto Rico Office of Energy, and the University of Puerto Rico. The owner and operator of the Río Cañas Dairy Farm, Mr. Antonio Ubarri, also made a considerable financial contribution to the project. Engineers Carmelo González and Jairo Lascarro were largely responsible for the design of the system, and Mr. Ronald Ramos, of RAMA Construction, Inc., did an excellent job with the construction of the system. Mr. Anastasio Morales of the U.S. Soil Conservation Service designed and oversaw construction of the storage pond. Two private firms contributed their services to the project. They were Bacardi Corporation, which performed chemical analyses of samples, and Spectron Caribe, Inc., which provided monitoring services on the engine-generator.

Valuable technical support was received from Messrs. Robert Breckenridge and Warren Thompson of EG&G, Idaho, Inc. and from the staffs of the other six DOE-funded EIFS projects. The project could not have been completed without the able assistance of technicians Thomas Sadler, Dennis Corales, and Carlos Rivera and the invaluable secretarial support of Mmes. Elba Cardona and Sonia García. Farm workers Messrs. Luis Díaz and José Robles were highly cooperative and very patient.

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# 1.0 INTRODUCTION

In response to rising fuel costs and uncertainty regarding future fuel supplies during the 1970's, the Office of Industrial Programs of the U.S. Department of Energy launched a program entitled the Energy Integrated Farm System (EIFS) program. The purpose of the EIFS program was to promote energy self-sufficiency in farming enterprises through a combination of energy conservation measures and the application of alternative-energy technologies. This latter goal was to be accomplished by on-farm integration of livestock, crops, and energy production systems. A total of seven projects, six from diverse geographical regions of the mainland U.S. (1-6) and one from Puerto Rico, received funding and were carried to completion. Four of these projects were located on dairy farms, two were on swine farms and one was on a cotton farm.

The University of Puerto Rico's Energy Integrated Dairy Farm (UPR-EIDF) project was located on one of the largest dairy farms in Puerto Rico, the Río Cañas Dairy Farm (Figure 1). The farm was in an area of low hills along the south central coast of Puerto Rico outside the town of Juana Díaz, near Ponce. Seasonal variations in temperature for the area were slight. Summer maxima were around 90°F, and winter maxima 85°F; summer minima were around 72°F, and winter minima 66°F. Rainfall for the area was limited and highly seasonal, and monthly averages for pan evaporation exceeded those for precipitation throughout the year (Figure 2). Annual rainfall averaged only 33 in., and approximately half of this rainfall was during the "rainy season" months of August, September, and October. Average annual pan evaporation was 87 in.

Figure 1. Sign at the entrance of the Río Cañas Dairy farm, site of the UPR-EIDF project.

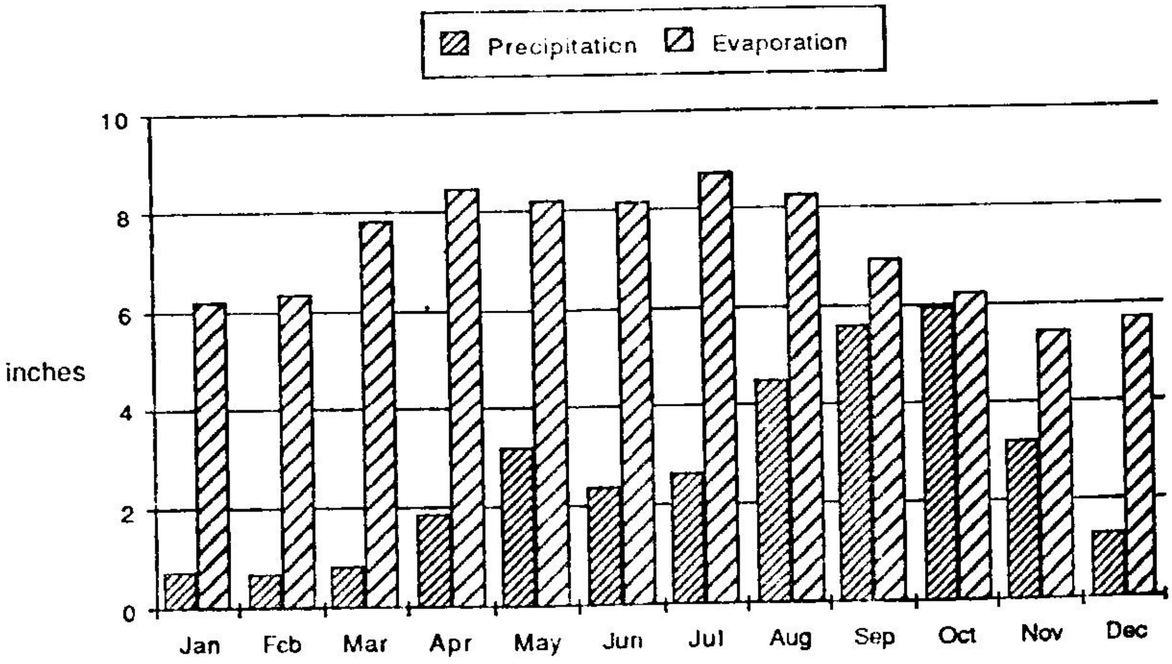


Figure 2. Average monthly precipitation and pan evaporation for the Juana Díaz area.

The Río Cañas Dairy Farm had a milking herd of 400 cows, which was divided into four groups based on production. Each group of milking cows was confined to a separate lot, while dry cows and heifers were turned out to pasture. Cows were milked twice daily, at 4 a.m. and 3 p.m., and daily milk production was 6,000 quarts. Milk was chilled to 38-40°F and sold unprocessed to a commercial dairy, which collected the milk on alternate days. Prior to milking, cows were driven into a holding area adjoining the milking parlor and washed. Water for the farm was supplied by two wells with a combined capacity of 210 gal/min.

Three critical aspects of Puerto Rico dairy farming are:

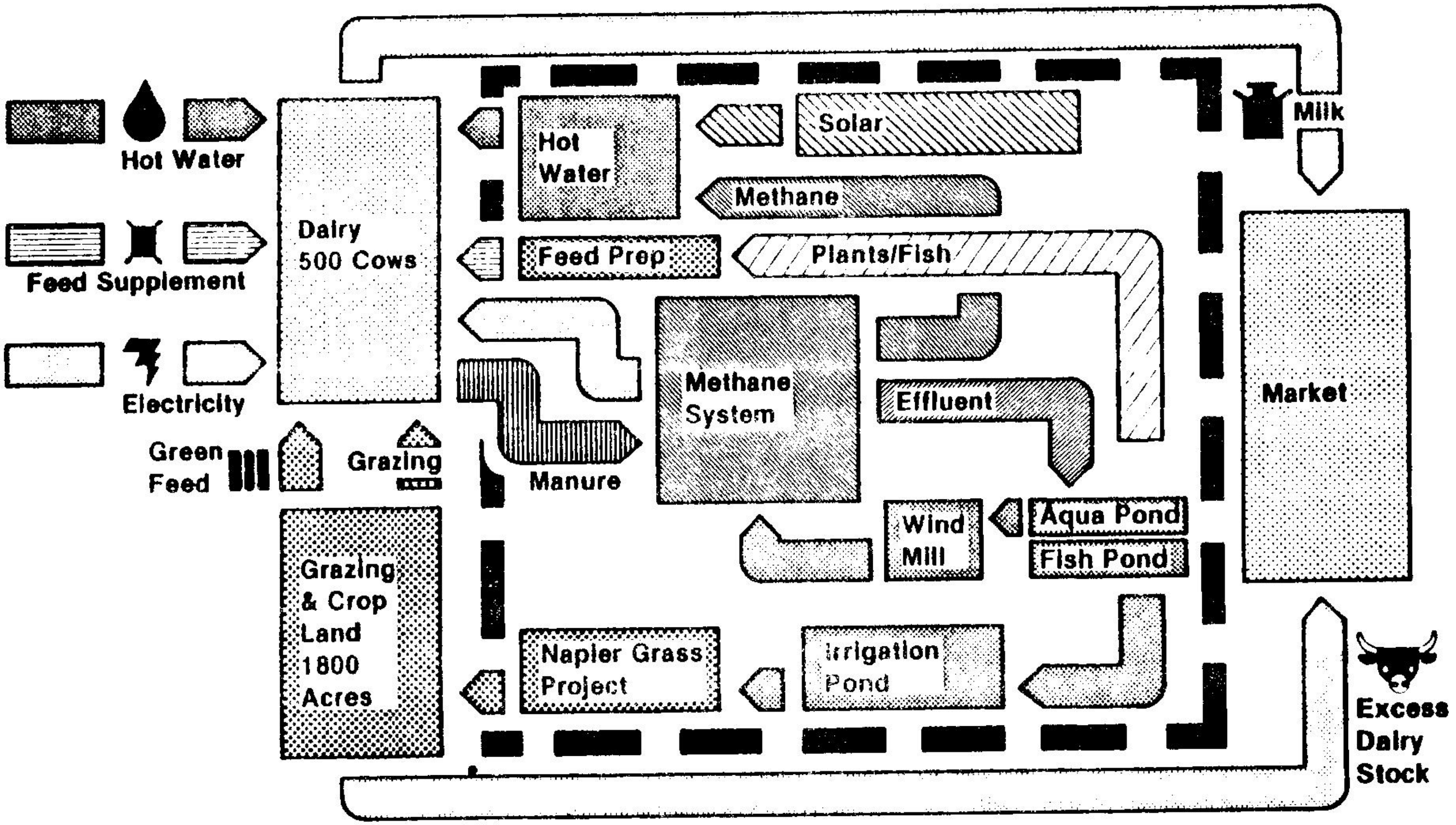
1. High Electrical Costs. Most electricity used on the farm was for the chilling of milk. At the outset of the UPR-EIDF project, electricity cost $0.12/kWh, and in the year prior to the initiation of the project the Río Cañas Dairy Farm spent $14,900 for electricity.
2. Farm Waste Disposal. If not managed properly, cow manure is a potential source of pollution. As such, its disposal was regulated by Puerto Rico Law No. 9, known as the Public Policy Environmental Act, approved on June 18, 1970, and enforced by the Puerto Rico Environmental Quality Board.
3. High Feed Costs. Feed costs represented between 35% and 50% of the cost of producing milk on the Río Cañas Dairy Farm. By reducing feed costs, farm profitability would increase.

The primary goal of the UPR-EIDF project was to combine a variety of onsite energy sources with state-of-the-art conservation practices to reduce the farm's dependence on external energy sources. To complement this goal, system design incorporated methods for water conservation, waste handling, and feed production.

## 2.0 PROJECT HISTORY

The Phase I Design Report for the UPR-EIDF project (7) was prepared while the project was under the leadership of Dr. A. G. Alexander. Figure 3 is a flow diagram of the system as proposed in the design report. The Statement of Work (8) prepared on the basis of the report called for five subsystems:

1. Anaerobic Digestion and Electrical Production. Dairy waste from the milking parlor and loafing barns was to be collected daily. Part of the waste was to be diverted to the greenfeed subsystem, and the remainder of the waste was to flow to two digesters. Biogas from the digesters was to fuel an engine-generator to produce electricity for dairy farm operations and sale to the public utility.
2. Farm Waste Management. Digester effluent was to be dewatered. Residual solids were to be dried with a solar drier and refed to the cows. The liquid fraction was to pass to algae and fish ponds for further purification.
3. Greenfeed Production and Usage. Using approximately 10% of the farm's raw manure, napier grass was to be grown as a cattle feed.
4. Solar and Wind Power. Solar energy was to be used to dry residual solids from the digester effluent along with algae and fish from the clarification ponds. Wind power was to be used to pump water from the ponds back to the anaerobic digestion subsystem where it would be used to dilute raw manure.



Ubarri-Blanes Farm

Figure 3. Flow diagram for the UPR-EIDF project as proposed in the Phase I Design Report.

5. Aquaculture. Algae and fish harvested from the ponds were to be dewatered and fed to the cows.

In June 1983, there was a change in program leadership. The new team reevaluated the Phase I Design Report and visited four private farms with biogas recovery systems. These farms were Fairgrove Farms in Sturgis, Michigan; Turkey Hill Dairy in Conestoga, Pennsylvania; Mason-Dixon Farm in Gettysburg, Pennsylvania; and Kaplan Industries in Bartow, Florida. Based on the analysis of the design report, experiences of the four farms visited, and discussions with the owner of the Río Cañas Dairy Farm, the new team modified subsystems one and three (these modifications will be discussed in the text) and eliminated subsystems four and five. Appendix I discusses the reasons for eliminating subsystems four and five.

## 3.0 SYSTEM DESCRIPTION

### 3.1 Description of Farm

Prior to the initiation of the UPR-EIDF project, the Río Cañas Dairy Farm was a loosely-organized entity which had evolved over the past two decades from a small dairy farm with fewer than 100 cows to its present status as one of Puerto Rico's largest dairy farms. Environmental regulations, though similar to those in the mainland United States, were not strictly enforced, so disposal of animal wastes was not a major concern.

Two of the four loafing barns were paved, but cows had unrestricted access to large, surrounding dirt areas. The other two loafing barns were unpaved. Paved areas were cleaned once or twice a week with a John Deere model 301A tractor equipped with a front-loading bucket. Waste material was pushed off the edge of the pavement, and it accumulated there. Once or twice a year, heavy equipment was leased to remove accumulated manure from all four lots. This material was hauled to other parts of the farm and used as fill.

An estimated 5,000 to 6,000 gal of water was used daily for washing cows before milking and for washing milking equipment. This water then flowed to an oxidation pond, where it either evaporated, seeped into the soil, or overflowed into a nearby stream.

## 3.2 System Design Considerations

Underlying considerations in the system design were safety, simplicity and reliability, topography, the amount of recoverable manure, farm energy needs, and current farm management techniques.

### 3.2.1 Safety

Biogas, the gas produced by anaerobic digestion of natural organic material, is explosive and highly toxic to breathe. Biogas from cattle manure generally consists of 55 to 60% methane ($CH_4$), 35 to 40% carbon dioxide ($CO_2$) and trace amounts of hydrogen sulfide ($H_2S$). It has an energy content of 550 to 600 Btu/scf and is explosive when mixed with air at concentrations between 5 to 15% (9,10,11).

The carbon dioxide and hydrogen sulfide components of biogas are heavier than air, so they tend to accumulate in low areas with poor ventilation. This is dangerous because (a) hydrogen sulfide is toxic, causing respiratory paralysis at concentrations above 0.06%, and (b) the absence of oxygen poses the possibility of asphyxiation (9). The potential dangers of biogas must be taken into consideration in both the design and operation of anaerobic digestion facilities, especially with regard to slurry retention tanks, manholes, and rooms where biogas may accumulate. Fences, grills, and proper ventilation must be provided when necessary.

### 3.2.2 Simplicity and Reliability

These two factors are generally mutually compatible. As the number of mechanical components in a system increases, the opportunity for failure also increases. It is important to design a system which is simple enough for the average farmhand to understand and operate and which requires a minimal number of man-hours to operate. It is also important to design a system which itself consumes a minimal amount of energy. If a system depends heavily on mechanical components such as pumps, it may end up consuming more energy than it produces.

### 3.2.3 Topography

As discussed above, the number of mechanical components in a system should be minimized. When possible, system components should be physically situated so that gravity-flow can be used for slurry movement.

### 3.2.4 Amount of Recoverable Manure

Tables on the amount of manure available from different types of livestock are provided in handbooks such as the Midwest Plan Service's "Livestock

Waste Facilities Handbook" (10). However, design of a system should be based on an estimate of recoverable manure rather than available manure. This is especially important for farms where cows are not completely confined or for farms with poor manure recovery facilities.

### 3.2.5 Farm Energy Needs

With an anaerobic digestion system, a primary consideration is how to use the biogas produced. Alternatives for biogas use include direct combustion to provide heat, fueling an absorption refrigeration system, or fueling an engine-generator to produce electricity. How biogas is used depends on the energy needs of the farm. If biogas is to be used to generate electricity and if estimated biogas production exceeds what is needed to produce electricity for the farm, there are two approaches to sizing the engine-generator. The engine-generator can be sized to use all available biogas with the excess electricity sold back to the public utility, or it can be sized according to needs of the farm with excess gas either flared or used elsewhere.

### 3.2.6 Current Farm Management Techniques

Current farm practices should be taken into consideration for two reasons:

1. To a large extent, the system must be configured on the basis of current farm practices. For example, design of manure handling facilities and the digester will vary depending on manure recovery practices.

2. Successful implementation of the system depends on minimizing its impact on current farm practices. If system operation demands radical restructuring of farm management techniques, the chances of its successful implementation are greatly reduced.

## 3.3 System Design

Figure 4 is a flow diagram of the UPR-EIDF system; Figure 5 is a schematic diagram showing relative positioning of the system components; and Figure 6 is a piping schematic which also shows elevations of the system components. The system was subdivided into three closely-integrated subsystems: Anaerobic Digestion and Electrical Production, Farm Waste Management and Greenfeed Production and Usage.

### 3.3.1 Anaerobic Digestion and Electrical Production

Manure from four loafing barns was collected and transported to a centrally-located mixing sump where it was diluted with wash water from the milking parlor and homogenized. Homogenized slurry was then pumped to two anaerobic digesters arranged in parallel. Biogas produced by the anaerobic digestion of the manure was used to fuel an engine-generator set which produced electricity for farm usage and for sale to the utility company. Heat was recovered from the cooling water of the engine-generator and used to heat the digesters.

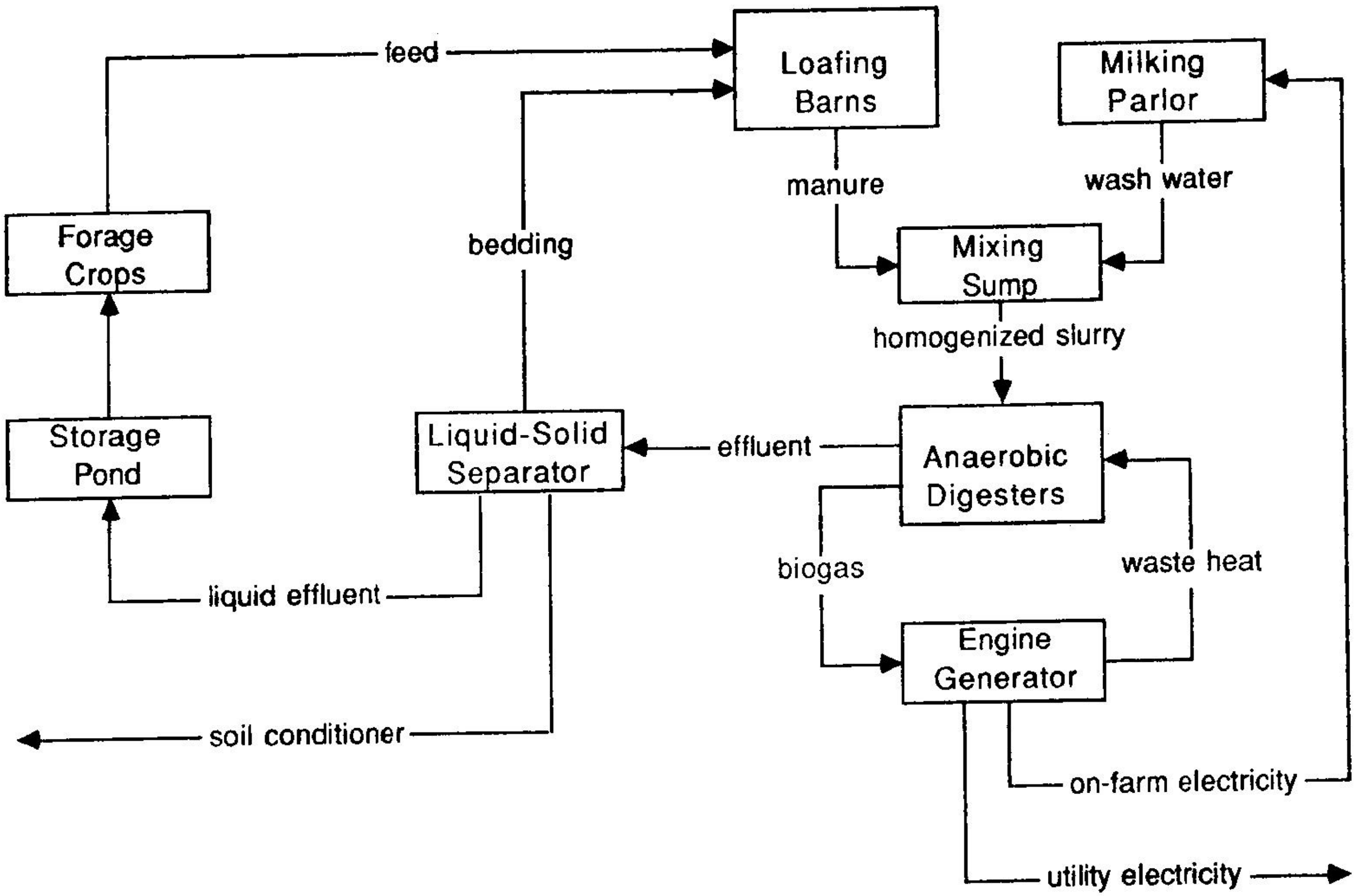


Figure 4. Flow diagram for the UPR-EIDF project.

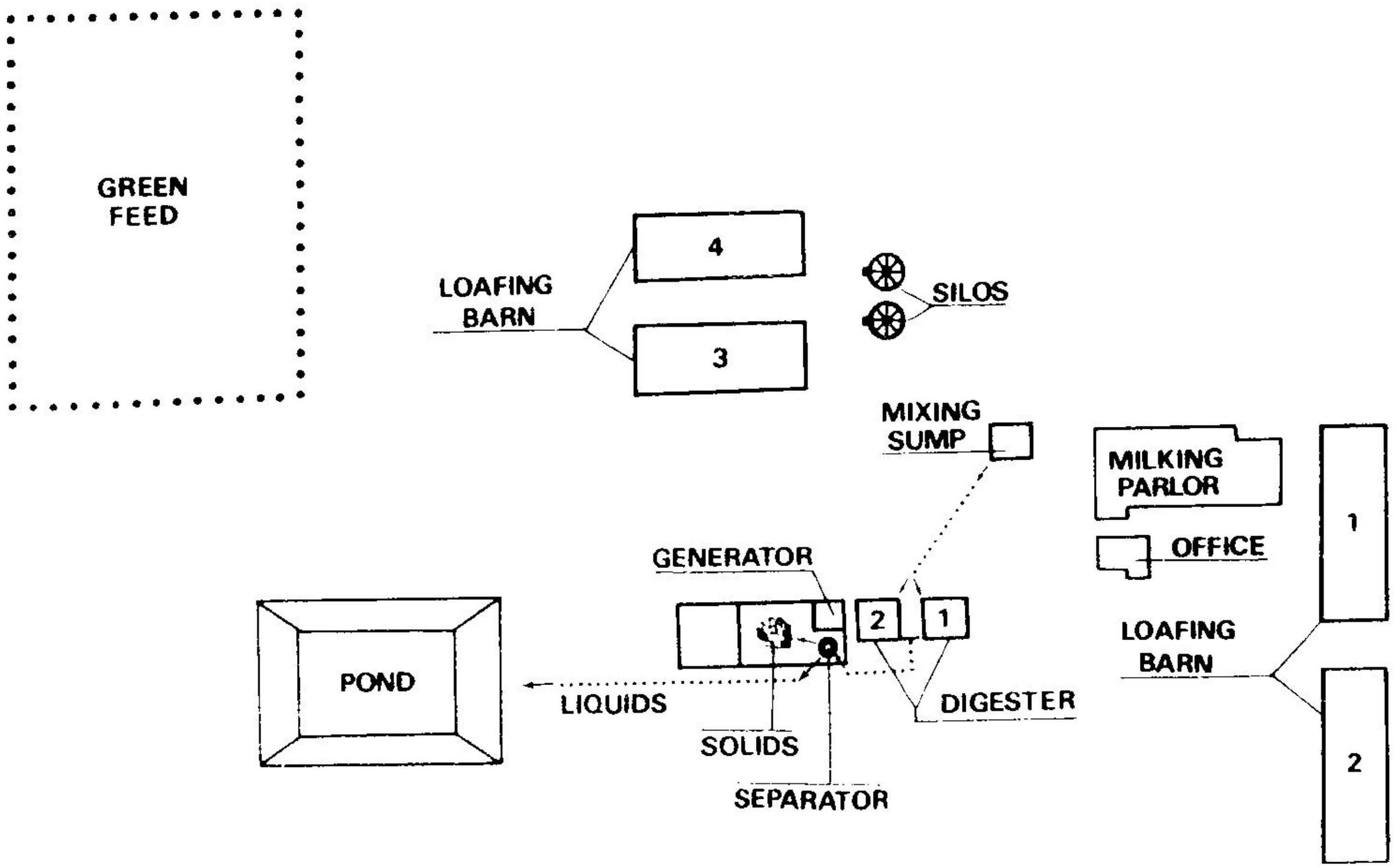


Figure 5. Diagram showing relative placement of the major components of the UPR-EIDF project.

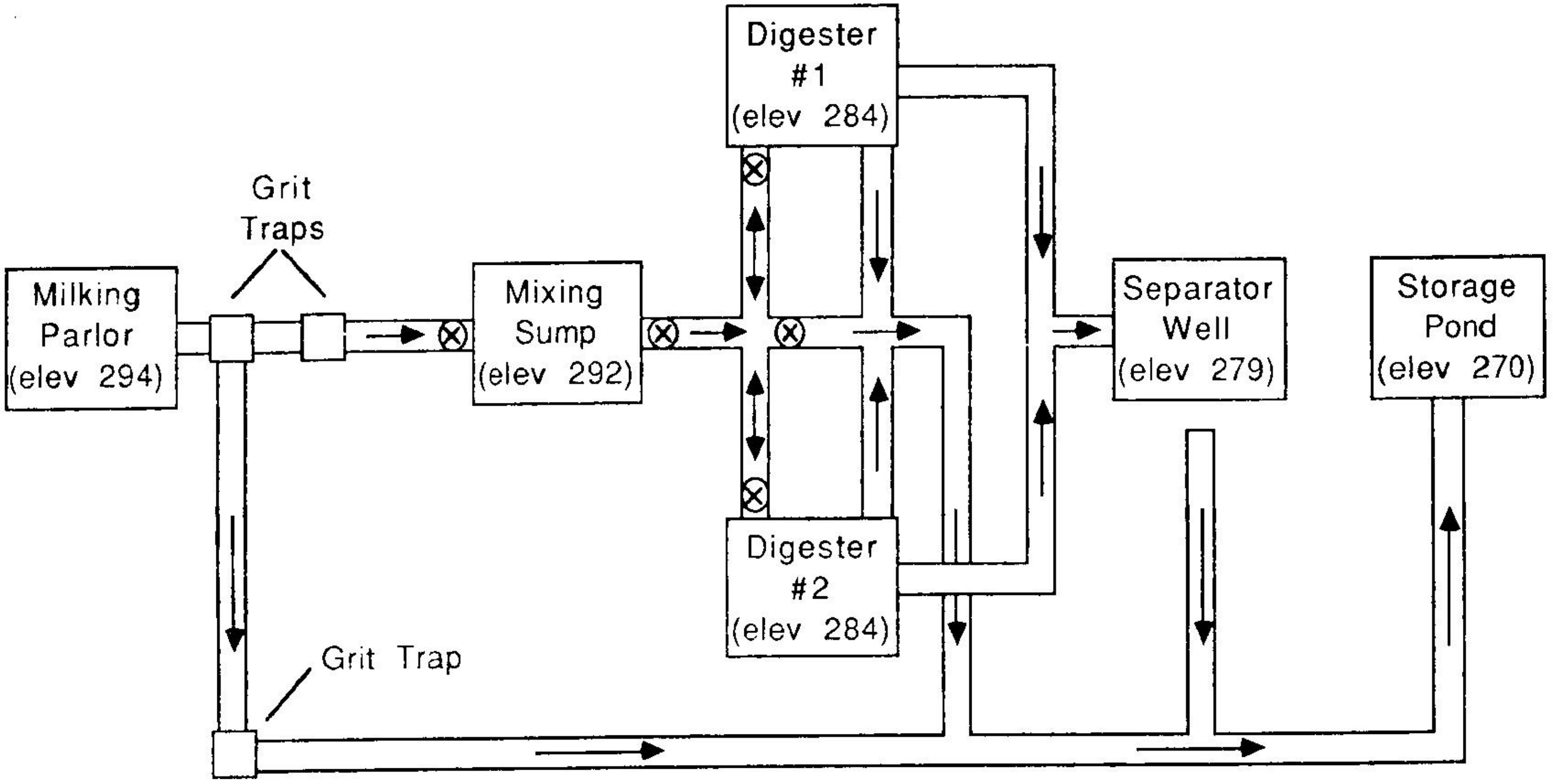


Figure 6. Piping Schematic for the UPR-EIDF project. Most flow was by gravity, and elevations are shown in parentheses.

### 3.3.2 Farm Waste Management

The two main sources of farm waste were manure from the loafing barns and wash water from the milking parlor. Milking parlor wash water contained manure and biodegradable detergents. Pollution characteristics of the manure and wash water were considerably reduced by the anaerobic digestion process, so, in addition to producing biogas, the anaerobic digesters served as the first stage of the Farm Waste Management subsystem. Digester effluent passed to a liquid-solid separator for solids recovery. Liquid fraction from the liquid-solid separator still had a high nutrient content, so it flowed to a storage pond for eventual land application to forage crops. Solid fraction from the separator was composted and either used as bedding material for the cows or marketed as soil conditioner.

### 3.3.3 Greenfeed Production and Usage

Forage material was grown on the farm using the nutrient-rich liquid fraction from the liquid-solid separator as a partial substitute for chemical fertilizers.

# 4.0 COMPONENT DESCRIPTION

## 4.1 General Design Considerations

Several factors need to be taken into consideration in the design of a manure-handling system. These include corrosion, grit, piping, and the use of valves.

### 4.1.1 Corrosion

Biogas is highly corrosive in the presence of oxygen due to its hydrogen sulfide component (12), so non-corrosive materials such as PVC and stainless steel were used when possible. Several vulnerable components were coated with Bitumastic Super Service Black (Koppers Company, Inc., Pittsburgh, Pennsylvania), a coal tar based product resistant to corrosive vapors.

### 4.1.2 Grit

A certain amount of grit will unavoidably accompany manure entering the system. Sources include grit tracked in by cows, windborne grit, and grit generated by scraping concrete floors. Removing accumulated grit from an anaerobic digester is rarely a trivial procedure. Depending on the digester design, cleaning may involve shutting the system down, draining the digester, and several days of unpleasant work. Two major considerations in the design of the system were to (a) minimize the amount of grit entering the digesters and (b) facilitate cleaning of the digesters and other components where grit would accumulate.

### 4.1.3 Piping

The importance of oversizing pipes and avoiding 90-degree elbows in a manure-handling system cannot be overemphasized since unclogging pipes can be costly and time-consuming. No matter how careful operating personnel are, foreign objects such as branches, blocks of wood, string, rags, or feed bags will enter the system occasionally. To minimize the chances for clogging, oversized pipes (generally 10-in.) were used, and no 90-degree elbows were installed. All bends in the piping were accomplished by using 45-degree elbows. Access tubes were installed at each elbow to facilitate cleanout should clogging occur.

### 4.1.4 Valves

The use of valves in a manure handling system is a questionable practice. In addition to being expensive, they are undoubtedly one of the more vulnerable parts of the system since they can easily clog or freeze. In the present system, valves were necessary to permit isolation of system components. Cast-iron gate valves of the same diameter as the associated piping were used, and access tubes were placed near each valve to facilitate cleaning. Valves below ground level were located in manholes covered with removable iron gratings to permit servicing. Valve handles were mounted on long stems, so it was not necessary to enter the manholes to manipulate valves (Figure 7). Manholes in manure handling systems are very dangerous since hydrogen sulfide gas tends to accumulate in them.

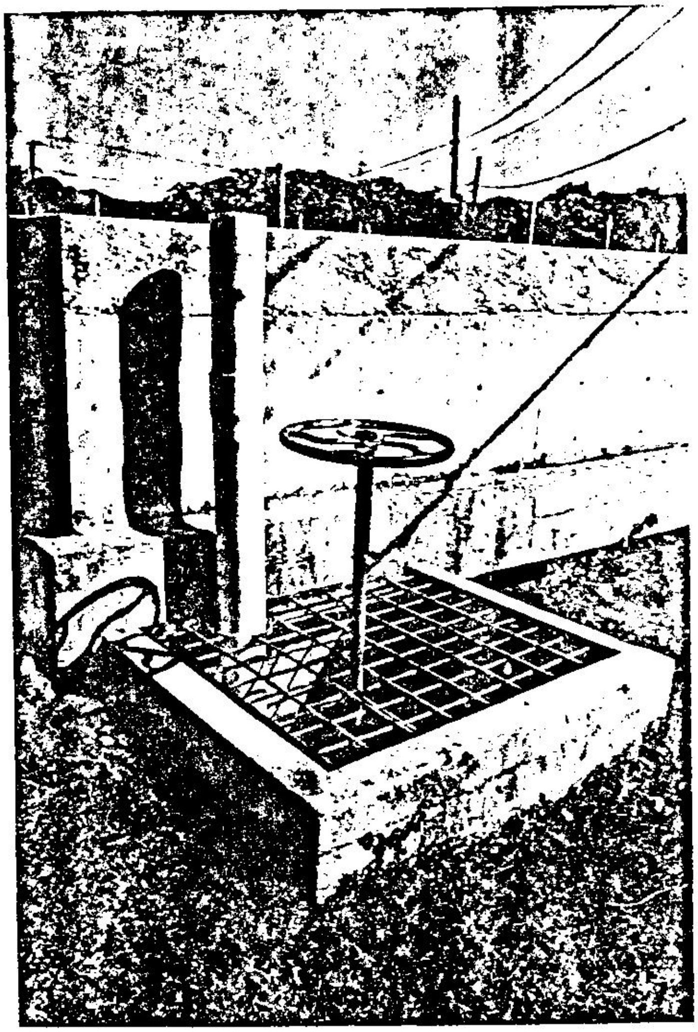


Figure 7. Valve manhole beside one of the digesters.

## 4.2 Anaerobic Digestion and Electrical Production

### 4.2.1 Design Criteria

Table 1 lists criteria used in sizing the system components. At the time the system was designed, the Río Cañas Dairy Farm had approximately 400 milking cows, but the farm owner expressed plans to increase his herd to 500 head in the near future. Therefore, the system was sized for 500 dairy cattle (7). Average cow weight was 1,200 lb, so approximately 100 lb/cow of manure

TABLE 1. DESIGN CRITERIA FOR THE UPR-EIDF PROJECT

| | |
|---|---|
| Dairy Herd Size | 500 cows |
| Average Cow Weight | 1,200 lb |
| Estimated Manure Production (8.2 lb/100 lb cow/day) | 100 lb/cow/day |
| Estimated Manure Recovery (75% recovery) | 75 lb/cow/day |
| Total Solids Recovery, 500 cows (12.7% solid content) | 4,800 lb/day |
| Volatile Solids Recovery, 500 cows (VS = 82.5% of TS) | 3,900 lb/day |
| Daily Manure Volume (@ 9.0 % solid content) | 6,400 gal |
| Biogas Production (5 $ft^3$/lb VS) | 19,600 $ft^3$/day |

would be available daily (10). Since cows were not completely confined to a paved surface, manure recovery was estimated at 75% of the total available manure. Manure was to be diluted to 9% total solids by weight, so the system was designed to handle an estimated 6,400 gal/day of slurry. Using a conversion rate of 5 $ft^3$ biogas per pound volatile solids loaded, biogas production was estimated at 19,600 $ft^3$/day.

### 4.2.2 Design of Subsystem Components

Figure 8 is a diagram showing the major components of the Anaerobic Digestion and Electrical Production subsystem. Raw manure was collected from four loafing barns and transported to a mixing sump where it was diluted

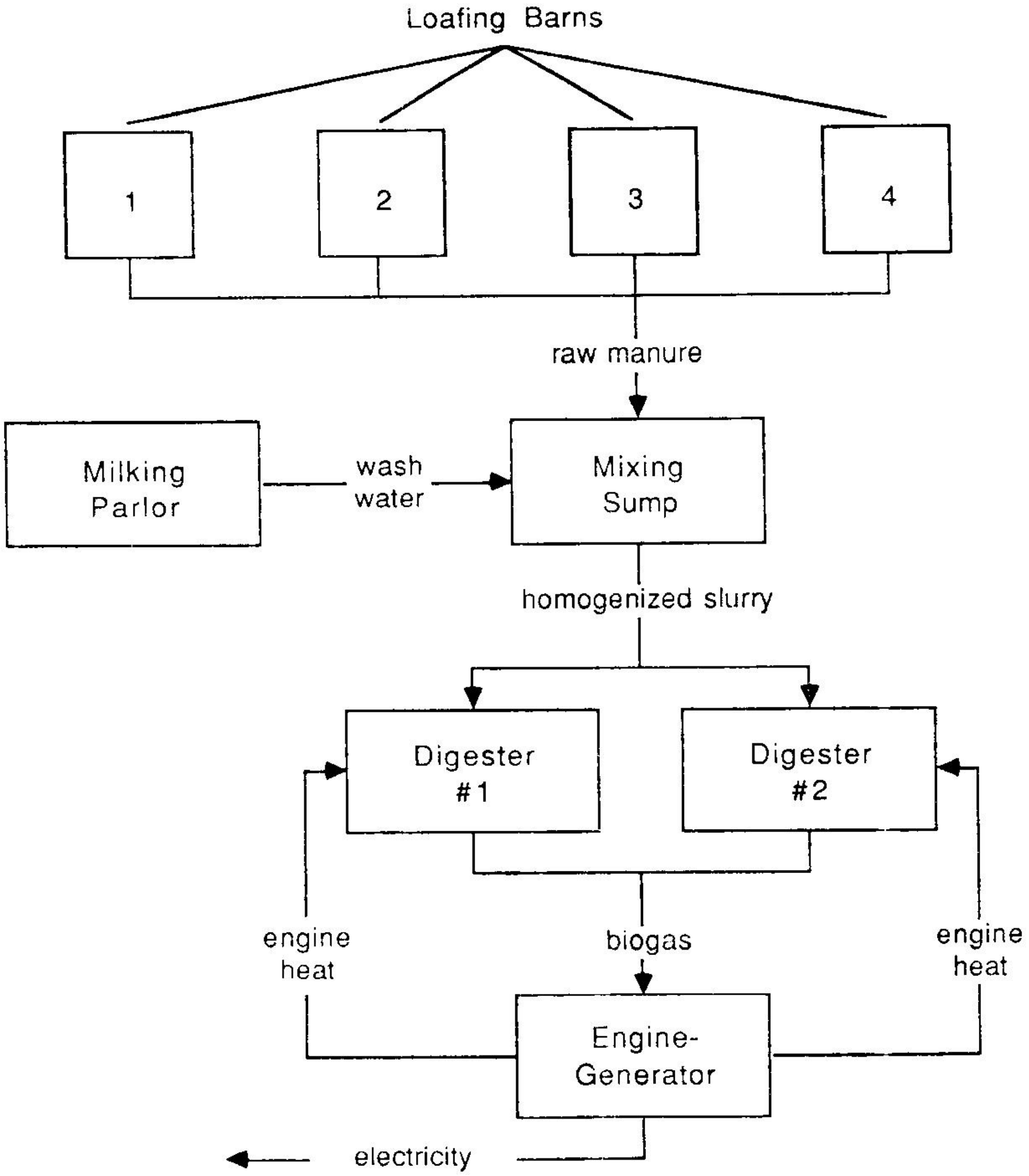


Figure 8. Major components of the Anaerobic Digestion and Electrical Production subsystem.

with wash water from the milking parlor and homogenized. From there, the homogenized slurry passed to two anaerobic digesters arranged in parallel. Biogas produced by anaerobic digestion of manure was used to fuel a synchronous engine-generator which produced electricity. Combustion heat from the engine was recovered and used to heat the digesters. The Anaerobic Digestion and Electrical Production subsystem was, in turn, subdivided into four areas: Manure Collection, Manure Preparation, Anaerobic Digestion, and Electrical Power Production.

4.2.2.1 Manure Collection. In the farm's existing mode of operation, only a small fraction of the manure could have been recovered. Milking cows were confined to four lots of between one-quarter and one-half acre each. Within each lot was a "loafing barn," which was an open-sided, shaded area where the feed troughs were located. Shading was provided either by zinc roofing or a plastic-mesh material. Water troughs were located outside the loafing barns in all four lots. Loafing barns 1 and 2 (see Figure 5) were paved, but cows moved freely from the pavement to the surrounding dirt areas (Figure 9). As a result, little manure was deposited on the pavement, and farm workers scraped these two loafing barns only once or twice a week. Loafing barns 3 and 4 had dirt floors, so no manure could be recovered from them.

To assure that the system had sufficient amounts of manure to function effectively, several modifications had to be made to dairy housing and to manure collection practices. These modifications were as follows:

1. A minimum of 7,500 $ft^2$ (60 $ft^2$ /cow) of concrete pavement was provided for each loafing barn.

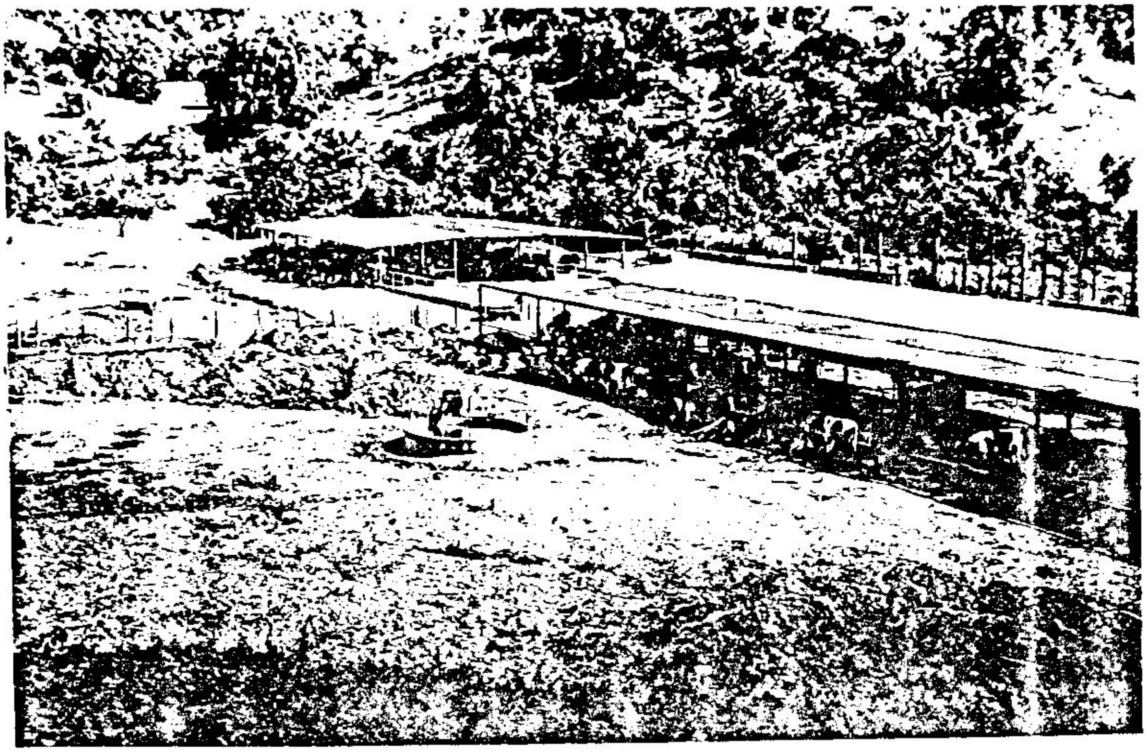


Figure 9. Loafing barns 1 and 2.

2. Each loafing barn was surrounded with a 10-in. high curb and a fence. The purpose of the curb was to contain manure and to prevent dirt from mixing with the manure. The fence was to allow for confinement of the cows to the pavement (Figure 10).
3. Manure storage boxes were constructed at one end of each loafing barn for temporary manure storage. The manure boxes were 10 ft wide,14 ft long, and had 4-ft high sides (Figure 11).
4. A water trough was constructed in each loafing barn.
5. Cows were to be confined to the paved loafing barns for most of the day. In the absence of bedded stalls, it is not healthy for cows to be on concrete all day, so the intent was to allow cows off the pavement for 2 to 4 hr daily.

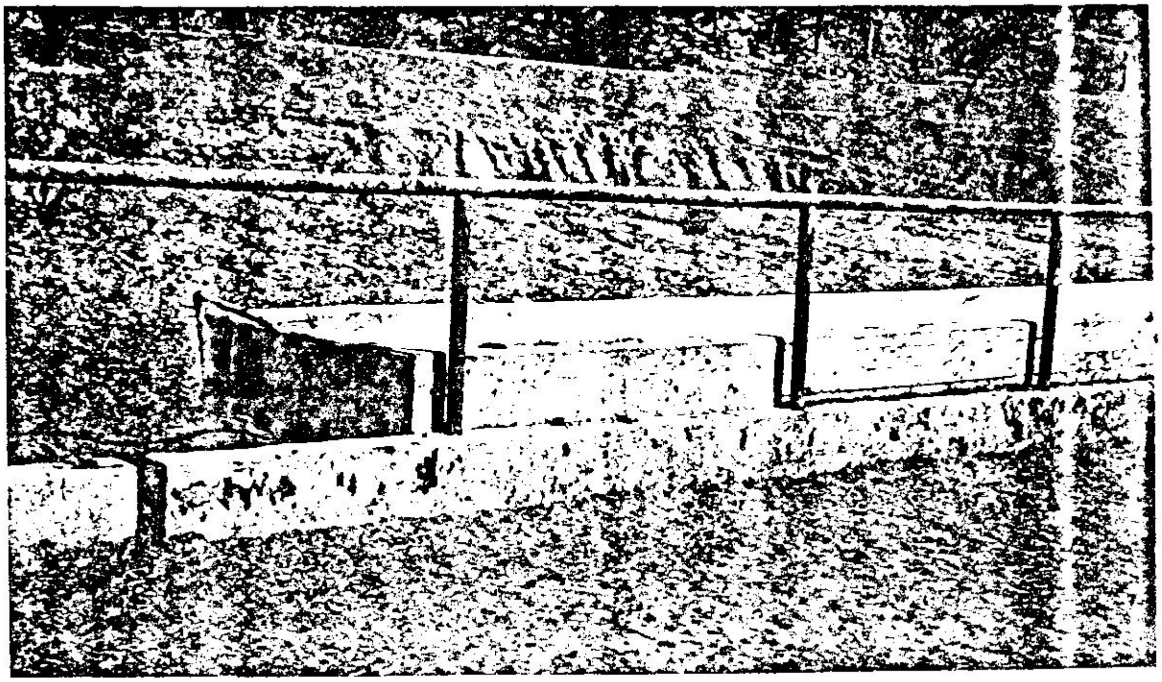


Figure 10. Curb and fence surrounding a paved loafing barn.

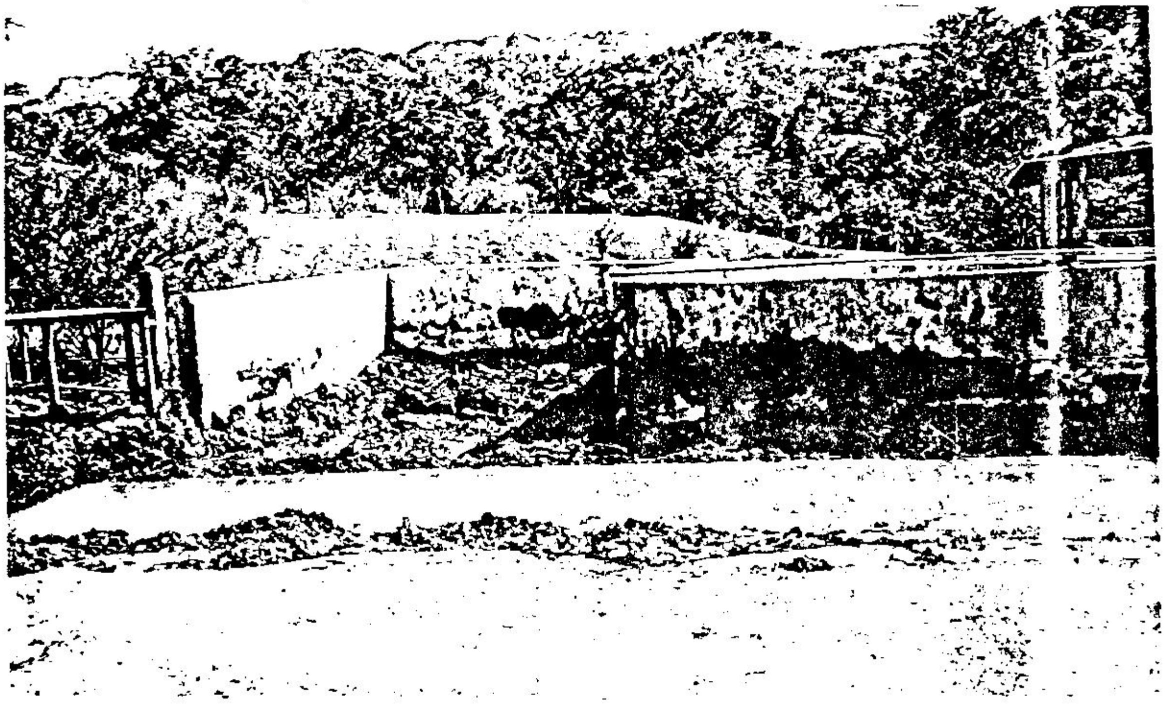


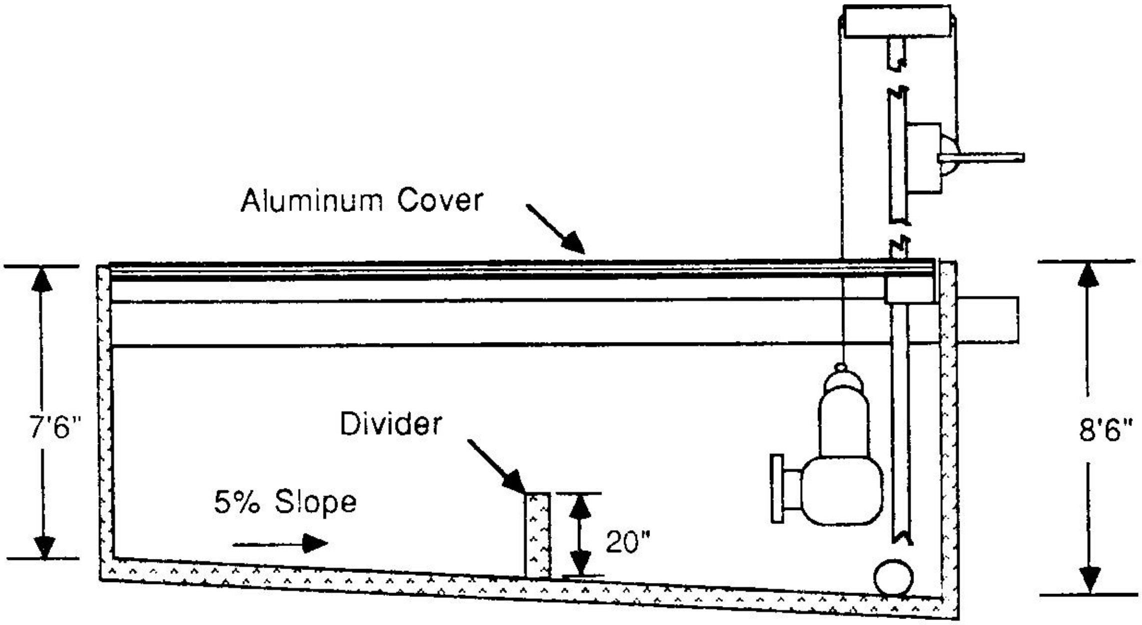
Figure 11. Manure box for temporary storage.

6. The loafing barns were to be scraped daily, and manure was to be hauled daily to the mixing sump.

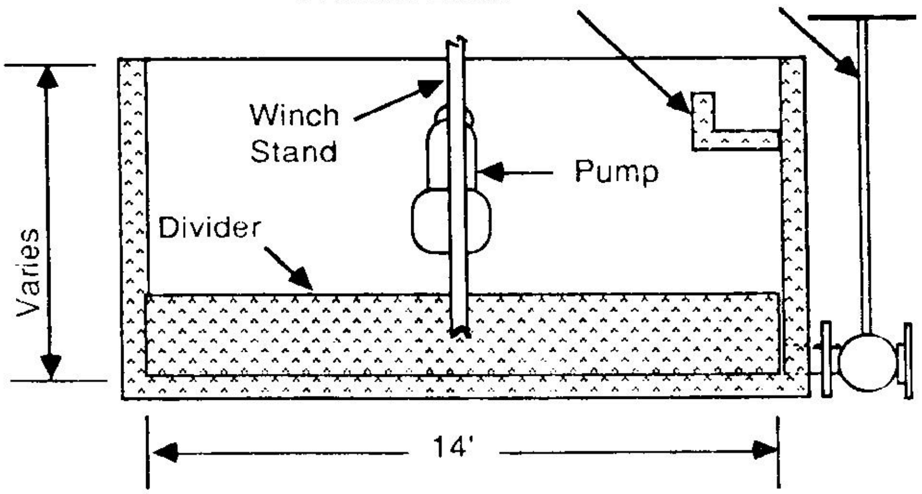
Wash water from the milking parlor was needed to dilute manure in the mixing sump, but it contained considerable amounts of grit. To reduce the amount of grit, two traps were installed in the piping system between the milking parlor and the mixing sump (Figure 6). These grit traps were 3 x 3 ft, 6 ft deep, and fitted with metal covers. Piping between the holding area of the milking parlor and the mixing sump consisted of 6-in. PVC pipe with a valve at the downhill end to control flow into the mixing sump. When the valve was closed, water passed to the storage pond through 10-in. pipe (Figure 6).

4.2.2.2 Manure Preparation. The design called for dilution of manure to 9% total solids by weight before loading into the digester. Total solids in fresh cow manure is approximately 12.7% (10); but since the loafing barns were open-sided, total solids of recovered manure was considerably higher due to evaporative losses. Table 2 summarizes calculations for the amount of dilution water needed to dilute manure at 35% total solids to the design level of 9% total solids. Estimated total solids recovery was 4,800 lb daily (Table 1), which translates to 1,600 gal of manure a day at 35% total solids or 6,400 gal of manure a day at 9% total solids. Therefore, a maximum of 4,800 gal of dilution water would be needed at the mixing sump each day. Since between 5,000 and 6,000 gal of wash water from the milking parlor were available every day, no additional dilution water would be needed.

The mixing sump (Figures 12a & 12b) performed three functions. It provided a site for dilution of partially dehydrated manure from the loafing barns; it was equipped with a cutter pump (20-hp, Flygt submersible cutter



Side View



End View

Figure 12a. End and side views of the mixing sump.

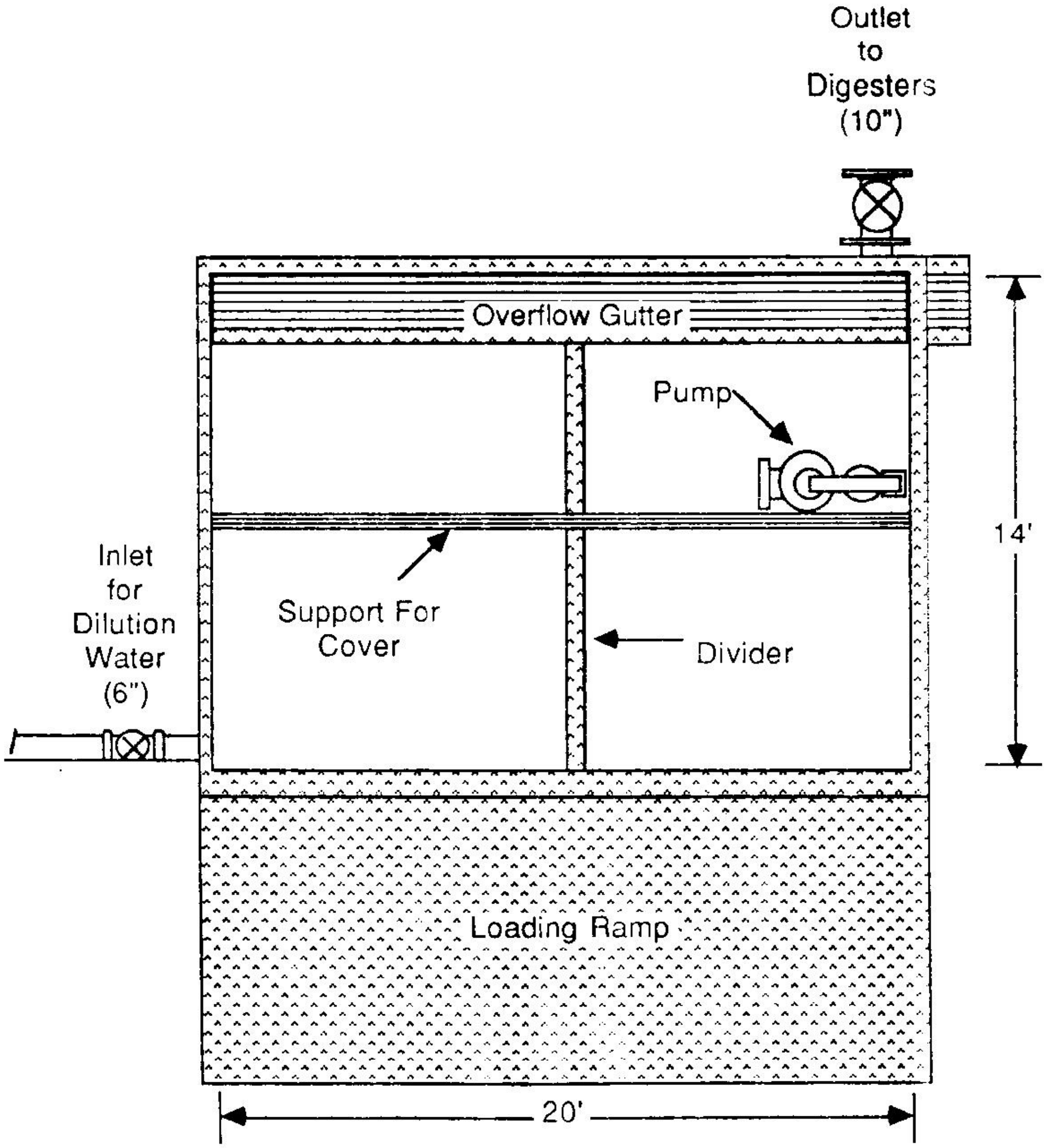


Figure 12b. Top view of mixing sump.

TABLE 2. MAXIMUM AMOUNT OF DILUTION WATER NEEDED

| | |
|---|---|
| Total solids (TS) of raw manure | 12.7% |
| TS of recovered manure (maximum) | 35.0% |
| Estimated daily TS recovery (from Table 1) | 4,800 lb |
| Estimated daily manure recovery (@ 35.0% TS) | 1,600 gal |
| Daily slurry volume (@ 9% TS) | 6,400 gal |
| Dilution water needed to reduce TS of manure to 9% | 4,800 gal |

pump, model 3152, type FP) to reduce long-stem forage material and homogenize the slurry; and it served as a settling tank where grit could settle out of the manure before the manure entered the digesters. The mixing sump was constructed of reinforced concrete. Walls were 8 in. thick, the floor was 12 in. thick and inside dimensions were 14 x 20 ft. The floor sloped at a 5% grade toward the drain. At the end where the drain was located, the wall was 8.5 ft high, while at the opposite end the wall was 7.5 ft high. Along one side of the mixing sump was an overflow gutter which maintained the slurry level at least 18 in. below the top of the mixing sump. Capacity of the mixing sump was 13,600 gal, or approximately 2-days' manure collection.

A concrete ramp 12 x 20 ft was constructed beside the mixing sump for unloading the manure (Figure 13). Manure was unloaded beside the inlet pipe from the milking parlor, and the outlet pipe to the digesters was located at the opposite end. The bottom of the outlet pipe was even with the floor to permit complete draining of the mixing sump when cleaning. A 20-in. high dividing wall was constructed across the middle of the mixing sump to prevent grit settling out of the manure and out of the dilution water from passing to the digesters. The mixing sump was covered with aluminum panels 38 in. wide and

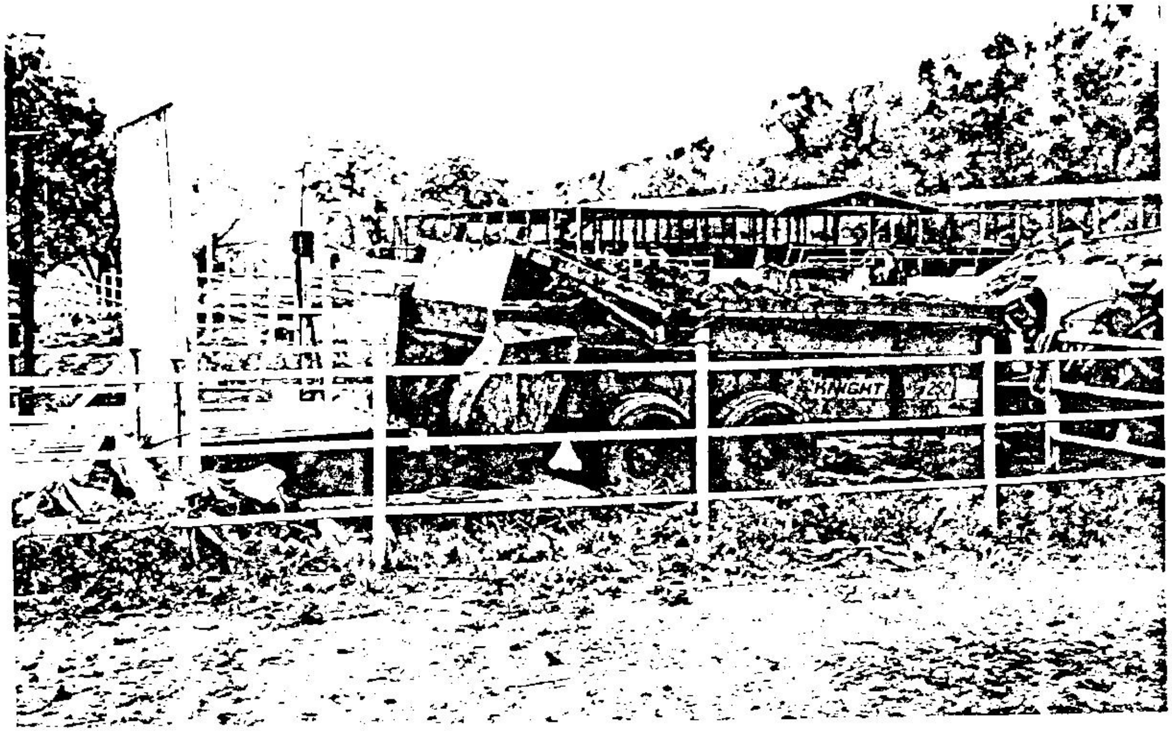


Figure 13. Manure being unloaded at the mixing sump.

15 ft long. The purpose of the cover was to (a) prevent humans or livestock from falling into the mixing sump, (b) prevent foreign objects from entering the sump, and (c) control evaporation and odors. The underside of the panels was coated with Koppers Super Service Black to retard corrosion, and a 4-in. galvanized pipe, which ran lengthwise down the middle of the mixing sump, helped support the panels. Where the manure was unloaded, several panels were joined together and hinged to form a lid 8 ft wide which could be raised and lowered (Figure 13).

Slurry passed to the digesters through an underground, 10-in. PVC pipe. A valve placed beside the mixing sump controlled flow from the mixing sump.

4.2.2.3 Anaerobic Digestion. Following is a list of considerations in the design of an anaerobic digester.

1. Size. Digester size is determined by the desired hydraulic retention time. Theoretically, the hydraulic retention time is the amount of time required to displace the contents of a digester. It can be calculated by dividing digester volume by the volume of material fed to it daily.

The digester is generally the most expensive component of an anaerobic system, so sizing of the digester is a compromise between cost and function. On the cost side, the primary consideration is digester efficiency, usually expressed in terms of cubic feet of biogas produced per cubic foot of digester. Maximum digester efficiencies occur with retention times of one to two weeks (13). With regard to function, an anaerobic digester performs two useful functions: biogas production, usually measured as cubic feet of biogas produced per pound of volatile solids fed to the digester; and stabilization of organic waste materials, usually expressed in terms of reduction of Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), or odors. Both biogas production and waste stabilization increase with longer retention times (9).

A further consideration in the sizing of an anaerobic digester is digester stability. Anaerobic digestion is basically a two-stage process where one group of bacteria (the "acid formers") reduces organic waste material to organic acids, and a second group of bacteria (the "methane producers") converts the organic acids to methane and carbon dioxide. Although the methane producers feed on organic acids, they are inhibited when acid concentrations in a digester become too high. For maximum methane production, a balance between the two groups of bacteria must exist. Longer retention times generally result in greater digester stability If retention times are too short, "organic overloading" can result. When organic overloading occurs, the acid formers predominate, pH in the digester falls, and methane production decreases drastically (9). Design retention time for the present system was approximately 3 weeks.

2. Configuration. A wide variety of digester configurations have been used throughout the world for the anaerobic processing of agricultural wastes (9, 13). At the Río Cañas Dairy, two modified plug-flow digesters were constructed.
3. Cover. The cover is a critical component of an anaerobic digester (14). It must be durable and form a gas-tight seal over the digester to prevent air from entering the digester and to prevent biogas from escaping. Both soft and hard covers have been used, but for this system concrete covers were placed on the digesters.
4. Inlet. The inlet should not be susceptible to clogging, and its design should promote an even flow of manure through the digester.
5. Outlet. The digester outlet must be provided with a gas seal, and designed so that it will not clog.
6. Cleanout. Sand and vegetative material will accumulate in the bottom of the digester, thereby reducing its effective volume. In the design of the digester, some provision should be made for the periodic removal of this material in a manner which is neither too time-consuming nor too expensive. A gravity cleanout is the best solution if feasible.
7. Heating. Optimum operating temperature (as determined by maximum biogas output) for an anaerobic digester under mesophilic conditions is between 95 and 104°F (15). Since very little heat is

released in the anaerobic degradation of organic wastes, heating is necessary to maintain an anaerobic digester at its optimum temperature.

8. Insulation. The digester may be insulated to minimize heat losses to the soil and atmosphere. Since this project was being conducted in a tropical area, no insulation was used.

9. Mixing. Mixing within the digester is optional depending on the design of the digester and the consistency of the feed material. Some investigators prefer mixing to promote contact between incoming manure and the digester bacteria and to ensure even temperature distribution throughout the digester. Mixing may be necessary to prevent the formation of a superficial scum layer which would prevent the escape of gas (9).

10. Gas Collection. The digester must be provided with piping to collect biogas produced within the digester. Gas piping should be large enough to minimize pressure losses within the piping itself, and it should be positioned well above the slurry level so that liquid or foam cannot enter and inhibit the passage of biogas.

11. Temperature Monitoring. One or more temperature-sensing devices should be placed within the digester.

12. Digester Sampling. If close monitoring of the digester is desired, some provision should be made for collection of gas samples and for easy removal of slurry samples from various parts of the digester.

13. Digester Penetration. Whenever the digester has to be penetrated by heating pipes, gas collection pipes, temperature sensing equipment, etc., the entry point must be gas-tight if it is above the slurry level, or water-tight if it is below the slurry level. A water-tight seal is much

easier to attain, but an entry below the slurry level is more difficult to service.

Two identical anaerobic digesters were used rather than a single larger digester in order to provide flexibility. Figure 14 is a three-dimensional view of a digester, while Figure 15 is a cross-sectional view of a digester. The digesters were square to maximize surface-to-volume ratio, thereby minimizing construction costs. They were 30 ft on a side with vertical walls 11.5 ft high and a floor which sloped at a 30-degree angle toward a central well 4 x 4 ft and 2.5 ft deep. The purpose of the sloping floor was so that grit settling from the slurry would tend to move down-slope and accumulate in the well, which was accessible from the outside by four, 6-in. cleanout pipes. The main body of the digesters was located below ground level, and, since this system was being installed in a geographical region where temperatures rarely fell below 65 °F, insulation was not installed.

In the original design, the digesters had fiber glass covers, and each digester had a volume of 70,000 gal. Design retention time was 22 days. After construction began, concrete covers were substituted for the fiber glass covers. This change was based on considerations of safety and durability, and also because no satisfactory method could be found for providing a gas seal between the fiber glass cover and the tank. With the change to a poured-concrete cover, the slurry level was raised so that the seam between the cover and the tank was submerged. A seal between the cover and the sides was provided by embedding PVC stripping vertically in the interface, but this seal was not gas-tight. Raising the slurry level increased digester capacities to approximately 88,000 gal each, yielding a design retention time of 28 days.

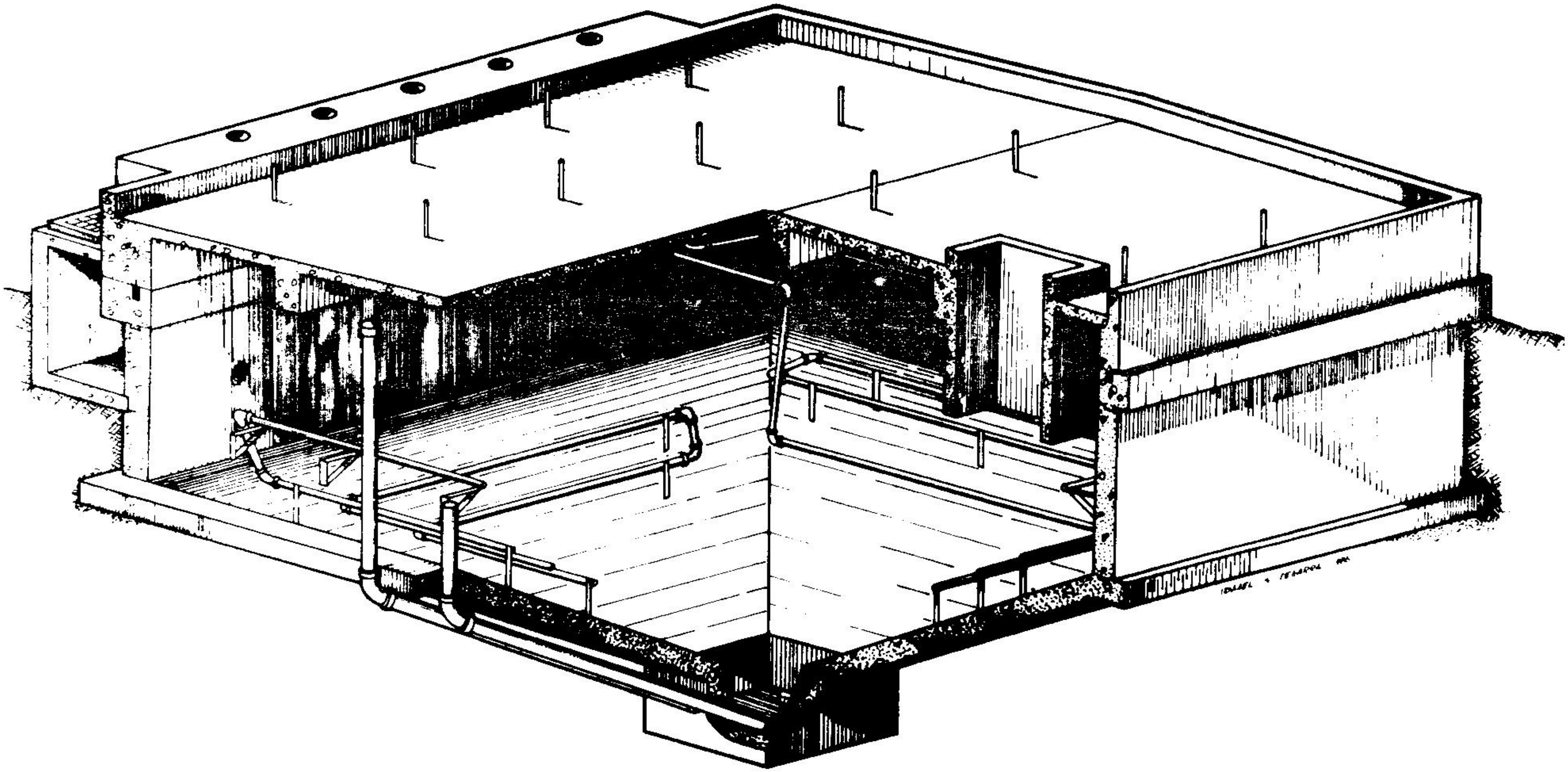


Figure 14. Three-dimensional, cut-away view of one of the anaerobic digesters.

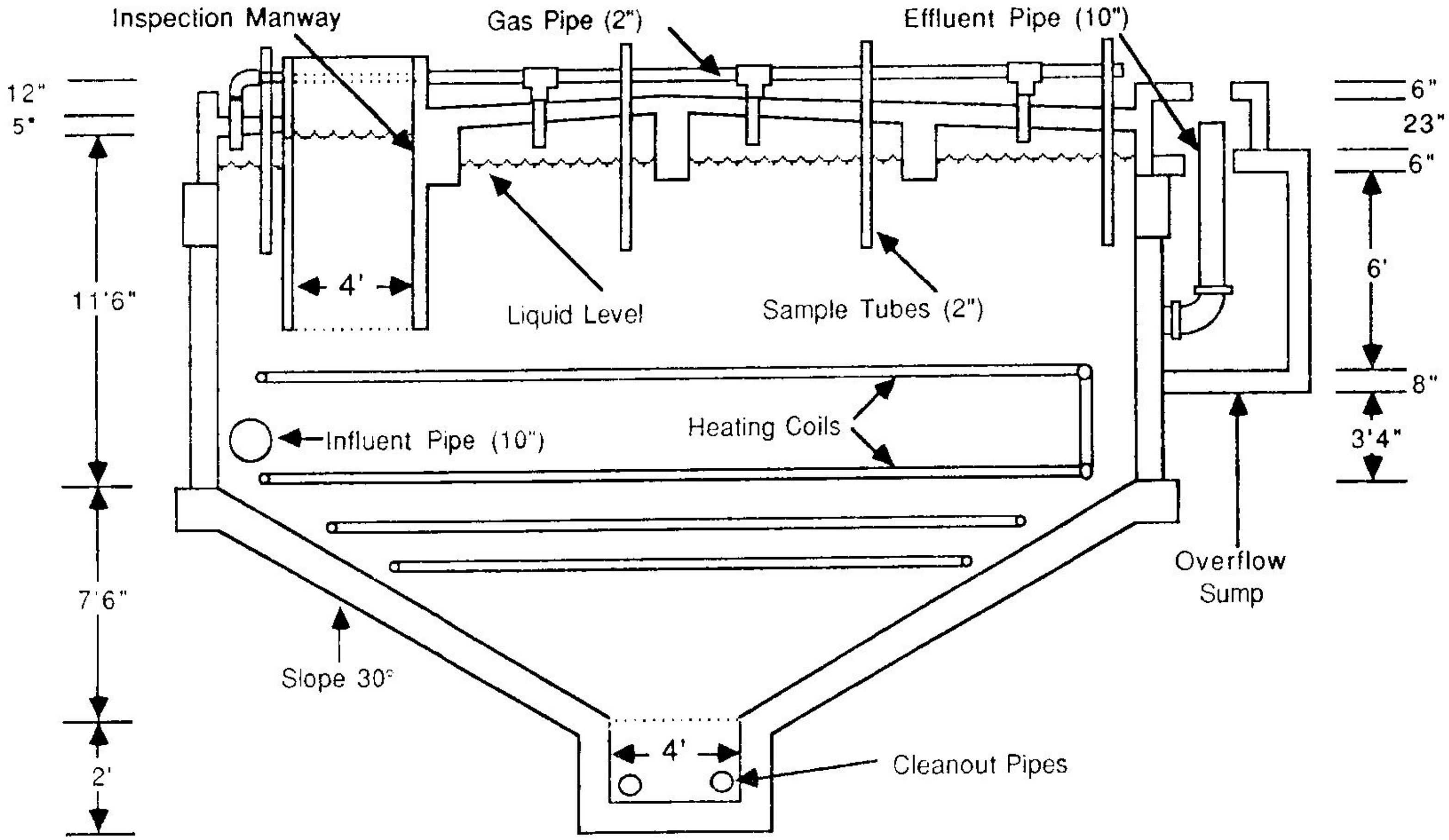


Figure 15. Cross-sectional view of an anaerobic digester.

The concrete covers were 5 in. thick with three support beams. Each support beam was 1 ft wide and extended down 2 ft into the digesters. To promote drainage, each cover sloped from the midline at a 1% grade. The covers were designed to withstand an internal gas pressure of 15 in. of water with a safety factor of at least 2.5. The upward force at 15 in. water column pressure is 78 lb/ft$^2$. The covers themselves weighed approximately 139,000 lb each, so they exerted a downward force of 154 lb/ft$^2$. To provide extra weight and to protect the concrete from direct sunlight, 1 ft of soil, contained by a perimeter curb 12 in. high and 6 in. wide, was placed on each cover. The soil increased downward force of the cover to 249 lb/ft$^2$.

To provide access to the digesters, 4 x 4-ft manways were installed in the concrete covers. The manways had gas baffles, and they were covered with removable iron grills. In addition, when the roof was poured, a total of 17 evenly-spaced holes were left in each cover. Four of these holes were fitted with gas collection pipes; one was used to mount a temperature sensor; and the remaining 12 holes were fitted with sample tubes. Figure 16 shows how the gas collection pipes and sample tubes were mounted. For the temperature sensor, a sample tube with the upper piece of PVC tube removed was used. A gas seal around the sample tubes and the gas collection pipes was provided by pouring Vulchem sealant (Mameco International, Cleveland, Ohio) around them. To stabilize the tubes and pipes, a collar of cement was poured around them after the Vulchem set. Four gas collection pipes were needed because the support beams of the digester covers divided the gas space of each digester into four compartments. These pipes were connected to a single header pipe which carried gas to the engine-generator. Gas pipes were installed with a 5% grade sloping back to the digesters so that condensate would drain back into the digesters (Figure 17).

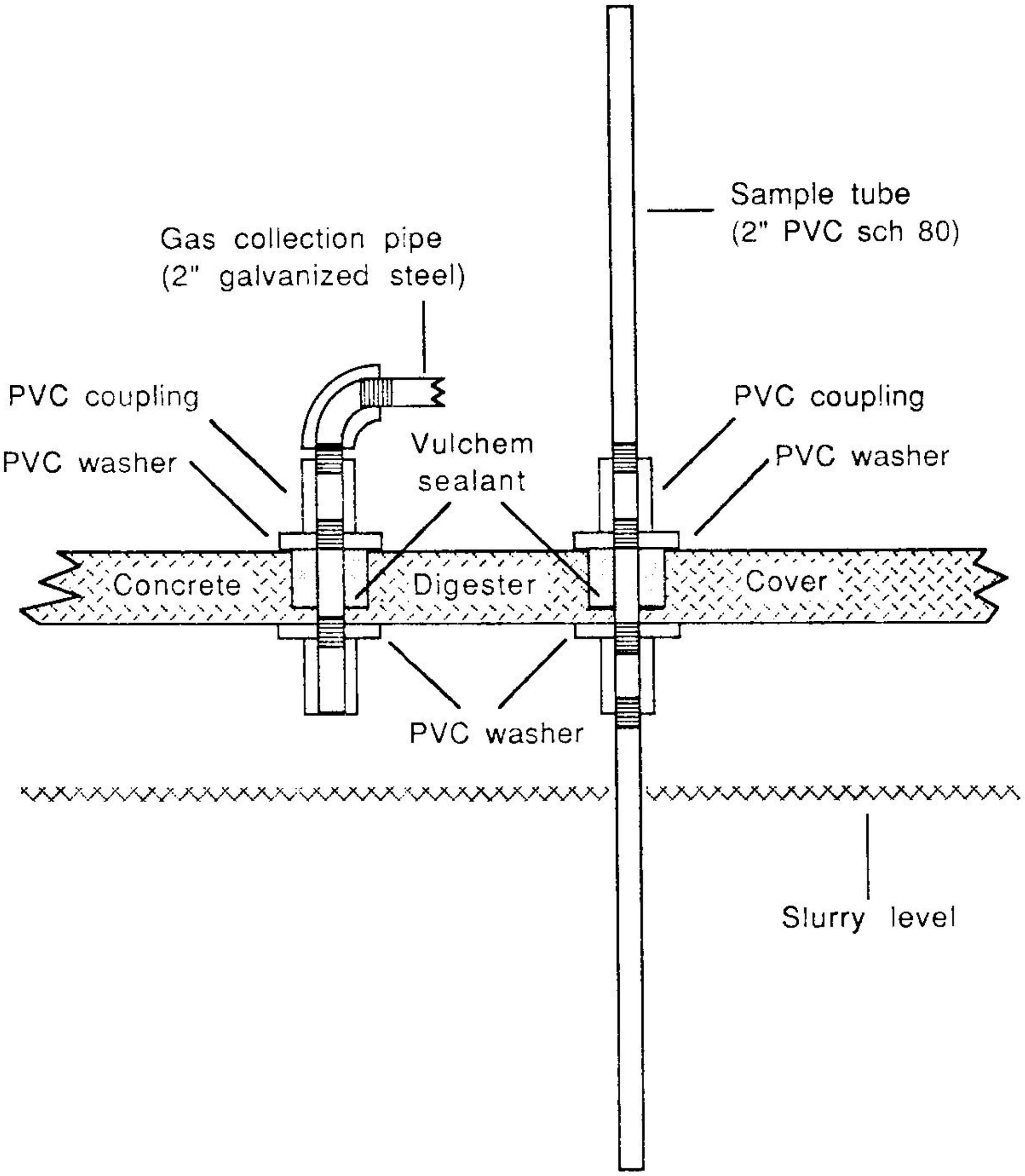


Figure 16. Mounting of a gas collection pipe and a sample tube in the digester cover.

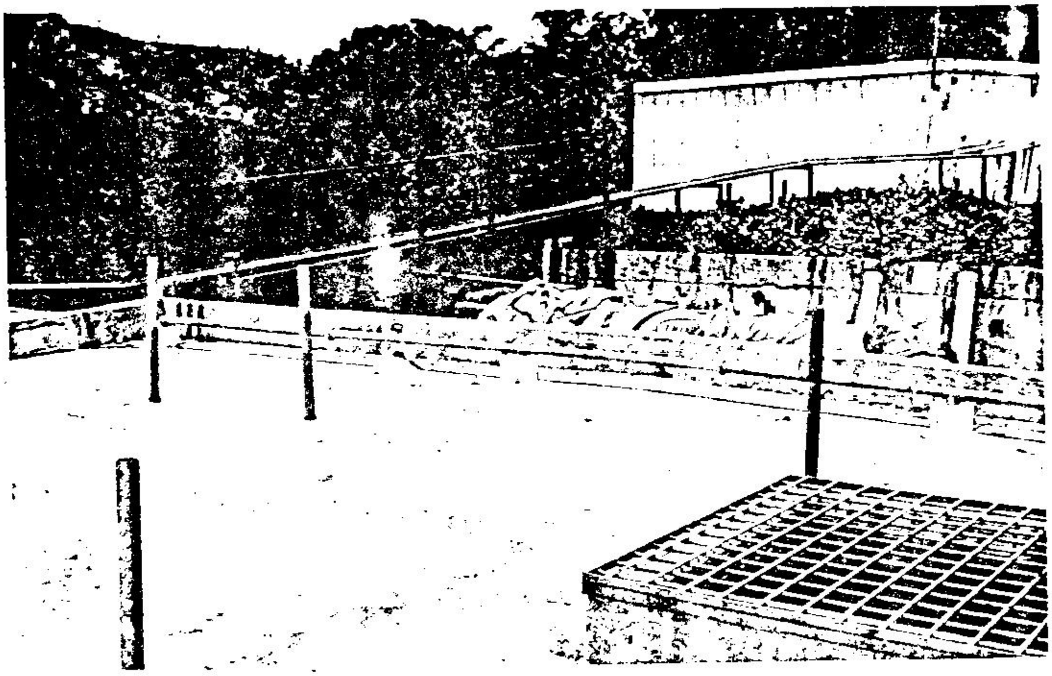


Figure 17. Gas collection pipes located along the edge of a digester, then sloping upwards to the generator room.

Slurry flowed to the digesters through 10-in. plastic piping, and bends toward the digesters were made by using two, 45-degree elbows rather than a single 90-degree elbow (Figure 18). A valve was located next to each digester to control slurry flow into, between, or out of the digesters. Slurry entered the digesters through an influent pipe which extended part-way across the digesters. These influent pipes caused some difficulties, which will be discussed below. Six, 10-in. effluent pipes were located along the side opposite the influent pipe. The tops of the effluent pipes were 1 in. below the roof of the digester to prevent slurry from entering the gas pipes. Therefore, slurry level was 16 in. below the covers when pressure within the digester was 15 in. of water. Effluent from each digester flowed into an overflow sump.

The original design called for a gas agitation system, and piping was installed in the digester for this purpose. However, based on experience at

Figure 18. Pipe junction between the two digesters. Pipe from the mixing sump is to the left. The two branches go to the digesters, and the bypass to the pond is on the right.

Fairgrove Farms and other farms with anaerobic digesters operated on cow manure, mixing did not appear to be necessary to prevent the formation of a scum layer if slurry was well homogenized and total solids of the slurry were maintained above 9%. Therefore, it was decided to operate the digesters without mixing.

Waste heat recovered from the engine-generator was used to heat the digesters. Separate piping systems went to the two digesters, and valves to control flow to each digester were mounted next to the engine-generator (Figure 19). Pipes between the engine-generator and the digesters were above ground and insulated with 1-in. neoprene. Heating pipes entered the digesters through an effluent tube. Approximately 330 ft of 2-in. galvanized pipe were arranged on the bottom and sides of each digester to transfer heat to the digester

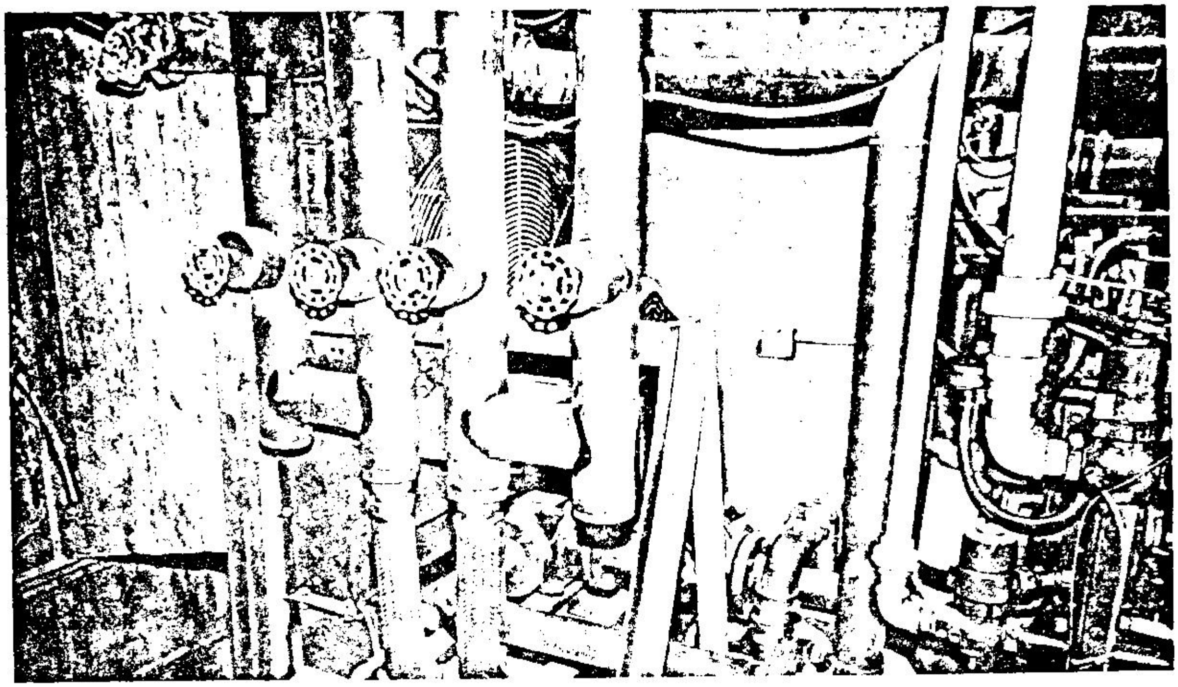


Figure 19. Valves controlling flow of hot water from the heat exchanger on the engine-generator to the digesters.

contents (Figures 14 and 15). Heating pipes were mounted on brackets which maintained the first tier 18 in. from the digester walls and the remaining three tiers 16 in. from the digester floors (Figure 20). Capacities of the heating systems were approximately 73 gal of water for digester 1 and 65 gal of water for digester 2, so a Model 110-P, Fill-Trol expansion tank (manufactured by Amtrol, Inc., acceptance volume of 2.4 gal), was installed at the highest point in each line.

4.2.2.4 Electrical Power Production. Estimated biogas production from the digesters was 19,600 $ft^3$/day (Table 1). Using a conservative figure of 1 kW for every 500 $ft^3$/day of biogas, there would be sufficient gas to fuel a 40 kW unit. Figure 21 shows the rate of electrical consumption throughout the day on the

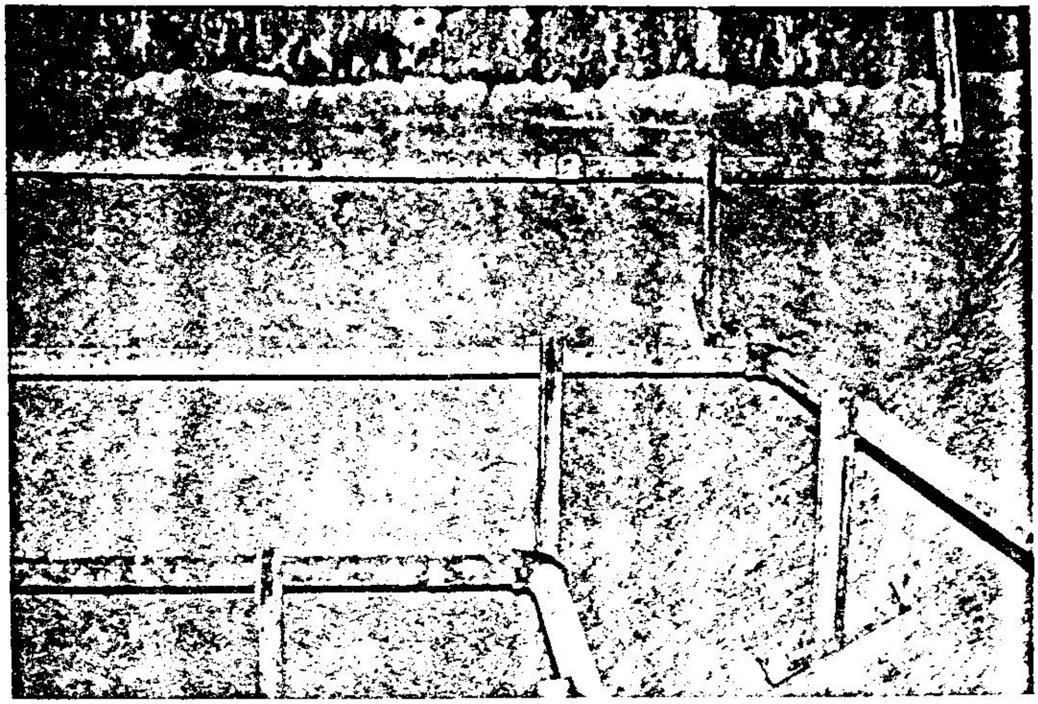


Figure 20. Heat exchanger pipes on sloping floor of a digester.

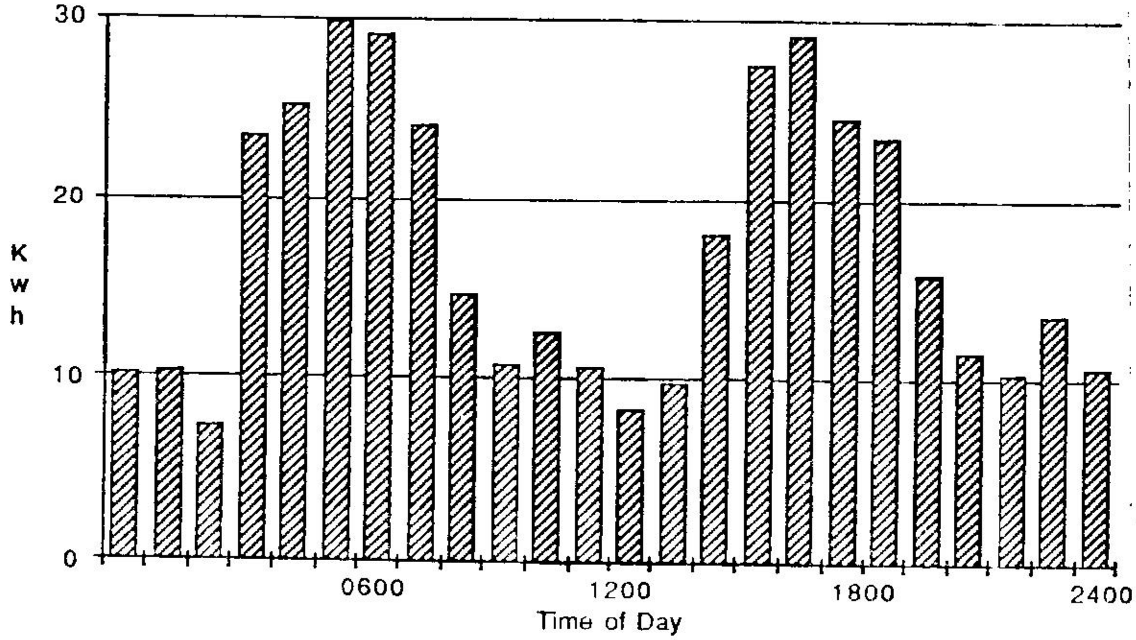


Figure 21. Electrical consumption on the Río Cañas Dairy Farm.

Río Cañas Dairy Farm. Base load was between 10 and 15 kW with two daily peaks of 30 to 35 kW which corresponded to the milking periods. Two approaches were considered in sizing the engine-generator:

1. Size the unit to use all biogas available and either sell excess electricity back to the utility or find an alternate use for it.
2. Size the unit to provide enough electricity to cover the base load of the farm and either vent excess gas or find an alternate use for it. During periods of peak farm consumption, some electricity would be purchased from the utility. By purchasing a 20-kW unit, the farmer could produce 85% of his electricity; with a 25-kW unit, he could produce about 95% of his electricity.

In Puerto Rico, electrical rates were uniform throughout the day. At the time the system was being designed, electricity cost $0.12/kWh, and the buy-back by the utility was $0.05/kWh. Under these conditions, there was little advantage to selling electricity to the utility. However, the farm owner was considering installing his own milk processing plant, so a 40-kW engine-generator was purchased.

The engine-generator was purchased from Perennial Energy, Inc. of West Plains, Missouri. It consisted of a Caterpillar 3304 natural gas engine modified to run on biogas and coupled with a Marathon generator. The Caterpillar 3304 was designed to run at 1800 rpm which would have yielded an electrical output of 55 kW, but by running the unit at 1200 rpm output was reduced to 40 kW. The engine-generator came equipped with the necessary electrical components for paralleling with the electrical utility; meters for monitoring engine performance, electrical output, and biogas pressure; and a safety system which automatically shut the engine down in the event of low biogas pressure, engine overheating, engine overspeed, low engine oil level or pressure, low water level, generator overload, or improper line voltage. If the engine shut down due to low biogas pressure or improper line voltage, it would restart when conditions normalized. It was not necessary to provide a blower to feed biogas to the engine since design pressure in the digesters was 15 in. of water.

Accessories to the unit were as follows:

1. Dual Fuel Carburetion. The engine could run on either biogas or propane gas. The capability to run on propane is useful at the outset when the digester is cold and biogas production may not be adequate to run the engine. Since there was no auxiliary heating source for the digesters, the engine could be run on propane until the digesters warmed and biogas production increased.
2. TrackerTrol. This was a mechanical system patented by Perennial which automatically linked electrical output with biogas production. It allowed the engine to continue running with reductions in biogas production as high as 50%. This is important since biogas production from anaerobic digesters shows considerable short-term fluctuations which are mainly associated with loading. The TrackerTrol provided an alternative to biogas storage facilities.
3. Heat Recovery and Digester Heating Packages. The heat recovery package recovered heat from the engine cooling water for use in heating the digesters. A pump mounted in front of the engine circulated warm water through the digester heating pipes. When heat was not being transferred to the digesters, a cooling fan was activated.

4. Oil Treatment System. A bypass oil filter with a chemically-treated, one-micron filter was mounted on the engine. The bypass filter was manufactured by the Nelson Division of Nelson Industries, Inc. Its purpose was to provide additional protection for the engine and lengthen the life of the engine oil by filtering and buffering it.
5. Gas Handling Unit. This unit was mounted on a separate skid and consisted of (a) two Roots 1.5M Gas Meters (Dresser Industries, Inc.) to monitor gas production in the two digesters, (b) a pressure relief valve set to vent gas when biogas pressure exceeded 18 in. water column pressure, (c) a particulate filter for the gas, (d) a valve for controlling the flow of biogas to the engine, and (e) water traps to remove condensate from the gas lines (Figure 22).
6. Battery Start. Battery-start was purchased on the manufacturer's recommendation. The alternative was using line voltage to start the unit.

The engine-generator and the gas handling unit were installed in a room within the separator building (Figure 23). The room was 14 x 20 ft and 12 ft high. The walls of the room were of 6-in. cinder block and the ceiling was of pressure-treated wood. Cross beams of the ceiling were 2 x 10 in. and covered by three-quarter-inch plywood. The underside of the ceiling was covered with 2-in. fiber glass insulation. Ventilation of the generator room is important to cool the engine and to prevent explosive biogas from accumulating in the room. In the back wall of the room, there was an opening 50 x 50 in. for the engine fan to exhaust (Figure 24). The opening was covered with one-quarter inch hardware

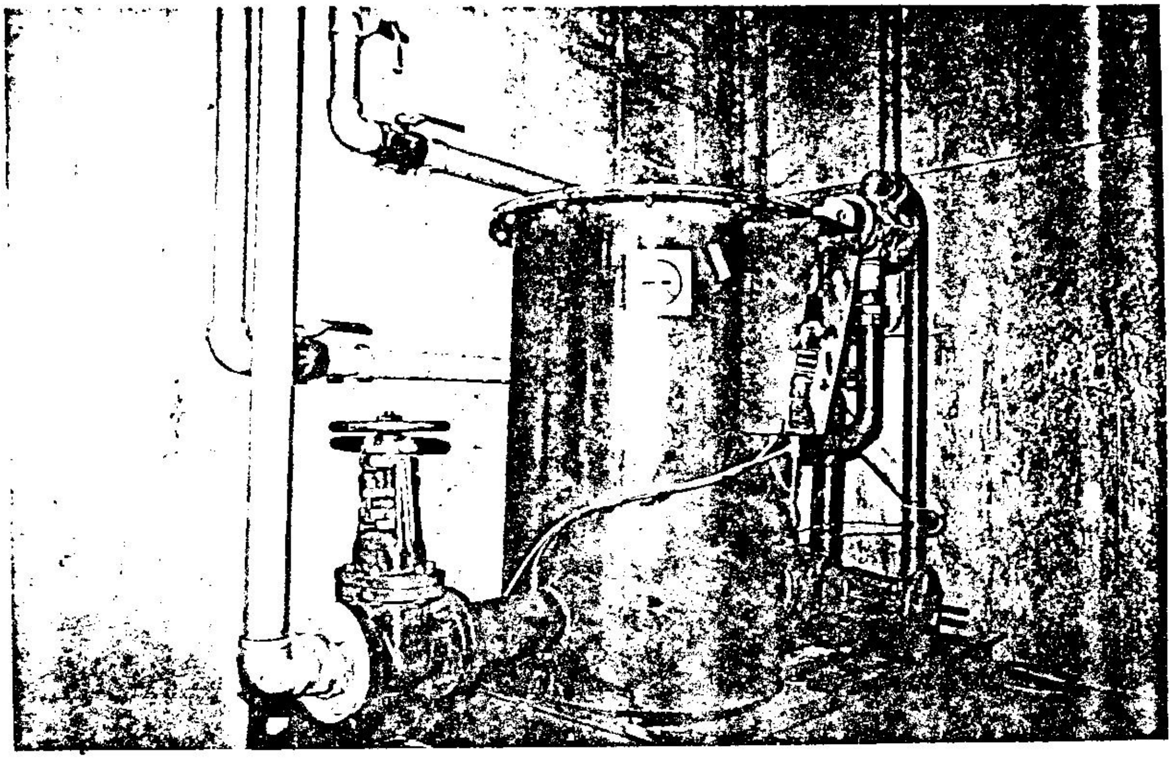


Figure 22. Gas handling unit.

Figure 23. Generator room within the separator building.

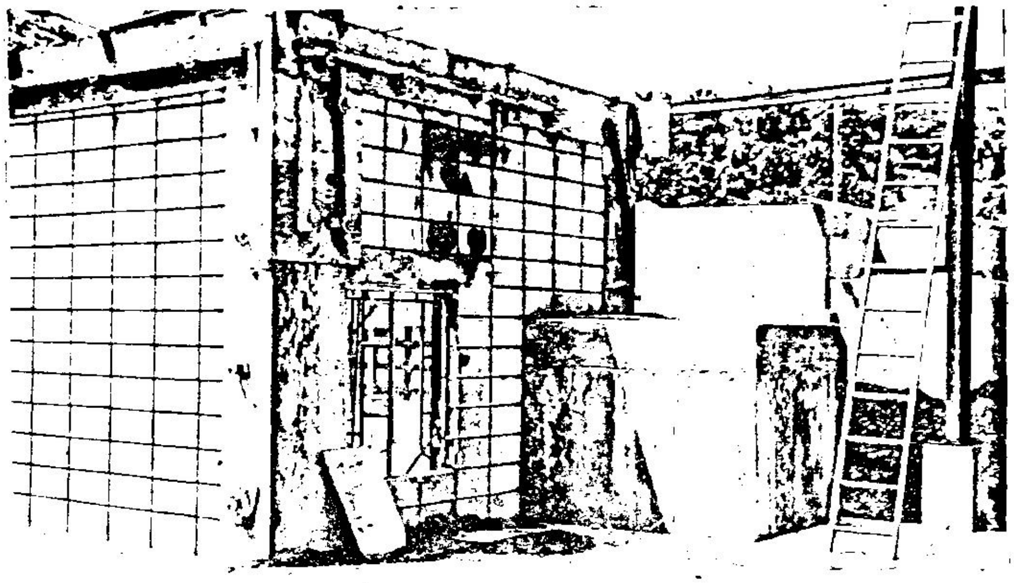


Figure 24. Window in back wall of generator room.

cloth. Since the fan was approximately 3 ft from the opening, a wooden duct was installed between them. A garage door 8 ft wide and 9 ft high was installed in the front wall, and a window 12 in. high with fixed louvers was placed above the door. Windows were not practical on either side of the room because of dust from the liquid-solid separator, so the opening above the door and the radiator opening provided the only ventilation for the room when the door was closed.

4.2.2.5 Subsystem Monitoring. To permit a comprehensive analysis of the project, the following variables were monitored:

1. Manure Recovery (in gallons) for each loafing barn
2. Volumetric Input to the Digesters

3. Hydraulic Retention Time (HRT)
4. Total Solids (TS) of samples from both the mixing sump and digester effluent (method from ref. 16)
5. Volatile Solids (VS) of samples from both the mixing sump and digester effluent (method from ref. 16)
6. Digester Temperature
7. Digester pH
8. Volatile Acids / Alkalinity Ratio of samples from the mixing sump, from within the digester, and from the digester effluent (method from ref. 16, nonstandard titration)
9. Biogas Production
   a. $ft^3$ biogas / hr (cfh)
   b. $ft^3$ biogas / lb VS fed
   c. $ft^3$ biogas / lb VS destroyed
   d. $ft^3$ biogas / day / $ft^3$ digester
10. Biogas Quality
    a. on-site measurement of $CO_2$ using a Fyrite $CO_2$ analyzer (Bacharach Instruments, Pittsburgh, Pennsylvania)
    b. laboratory measurement of $CH_4$, $CO_2$, $H_2S$, $N_2$, and $O_2$ using a Fisher Model 1200 Gas Partitioner
11. Biological Oxygen Demand (BOD) of samples from the mixing sump and from the digester effluent
12. Chemical Oxygen Demand (COD) of samples from the mixing sump and from the digester effluent

Table 3 lists where these variables were monitored and at what frequency.

TABLE 3. LIST OF VARIABLES MONITORED AND SAMPLE LOCATIONS

| Loafing Barns | Mixing Sump | Digester | Digester Overflow | Liquid-Solid Separator |
|---|---|---|---|---|
| Volume of manure recovered** | Biological oxygen demand*** | Biogas production** | Biological oxygen demand*** | Total solids* |
| | Chemical oxygen demand*** | Biogas quality** | Chemical oxygen demand*** | Volatile solids* |
| | Gallons of slurry fed to digesters** | pH*** | pH*** | |
| | pH*** | Temperature** | Total alkalinity*** | |
| | Total alkalinity*** | Total alkalinity*** | Total solids* | |
| | Total solids* | Total solids* | Volatile acids*** | |
| | Volatile acids*** | Volatile acids*** | Volatile solids* | |
| | Volatile solids* | Volatile solids* | | |

* Measured every time the digester was loaded

** Measured daily

*** Measured every three to four months

### 4.2.3 Operation and Performance

4.2.3.1 Manure Collection. To maximize manure recovery and minimize losses of moisture and volatile organics, manure should be collected frequently. However, the physical layout of the Río Cañas Dairy Farm was not well suited for efficient manure recovery. Loafing barns 1 and 2 were separated from the other two loafing barns by several hundred yards and three gates, so at least 15 minutes were lost in transit. In loafing barns 1 and 4, roof supports were inconveniently placed and had to be maneuvered around when scraping (Figure 25). Finally, placement of the original feed trough in loafing barn 4

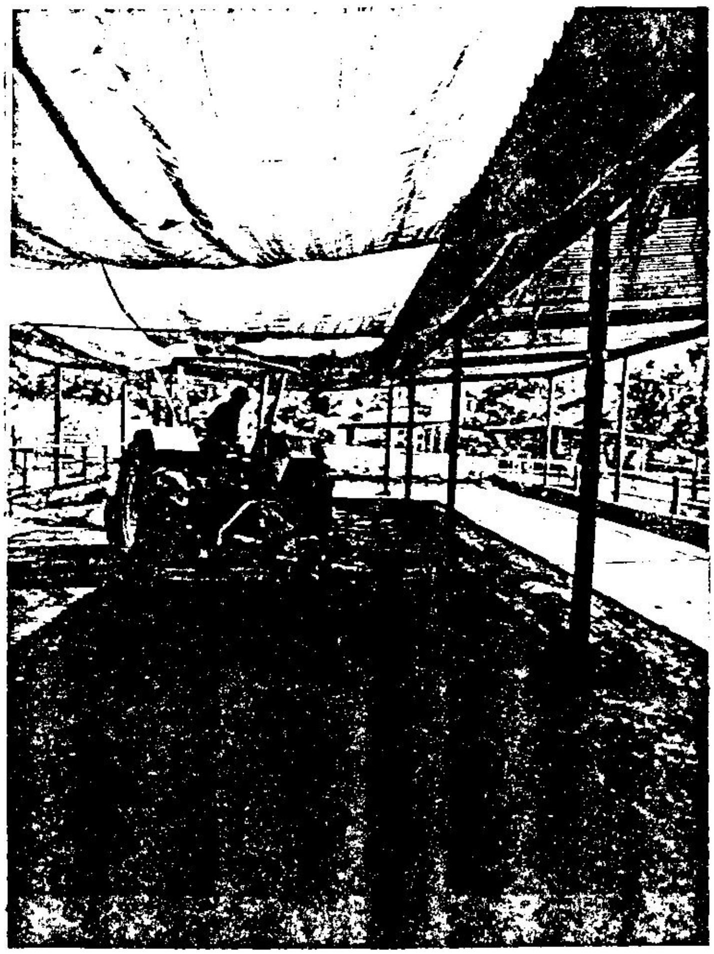


Figure 25. Roof supports in loafing barn 1.

made scraping difficult. Approximately 2 hours were required to scrape the four loafing barns, and it was not practical to scrape more than once a day. Manure was scraped using a John Deere model 301A equipped with a bucket in front and a scraper behind. This machine was highly suitable since it could be used for both scraping and loading manure. Once scraped, manure was loaded into a 120-ft$^3$, Knight manure spreader, transported to the mixing sump, and unloaded there (Figure 13).

Figure 26 presents average manure recovery, expressed as a monthly average of daily manure recovery per cow, for all four loafing barns from August 1984, when loading of the digesters began, through February 1986. Figures 27 through 30 give manure recovery for the individual loafing barns. Assuming a daily manure production of 100 lb/cow, less than 30% of the available manure was recovered during the first 6 months. There were three major reasons for this poor recovery:

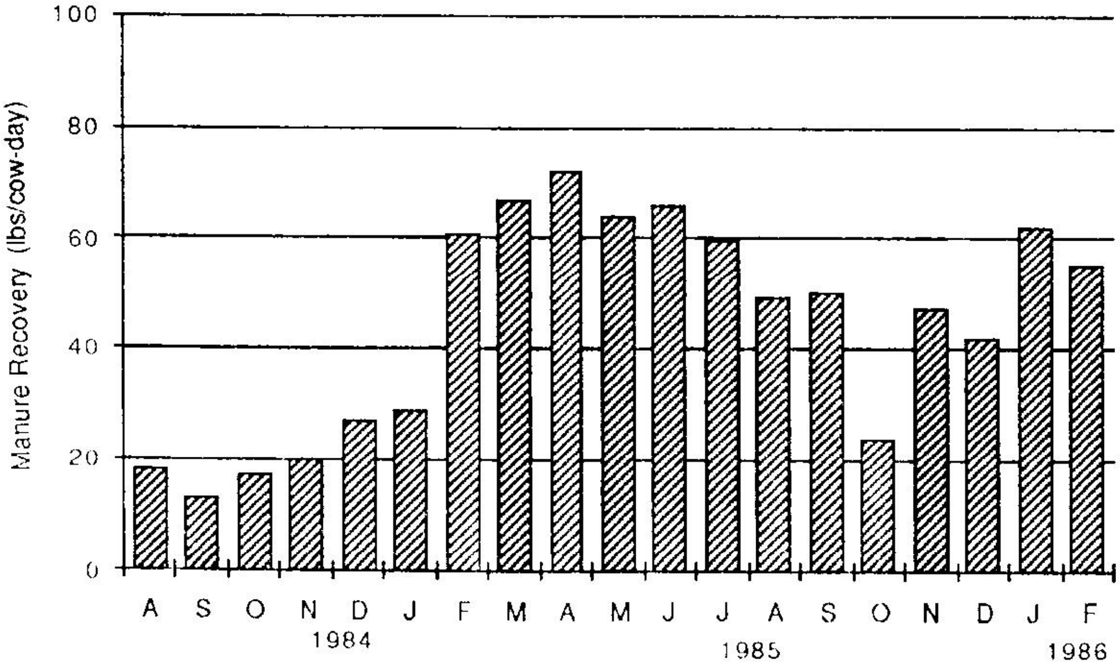


Figure 26. Average monthly manure recovery.

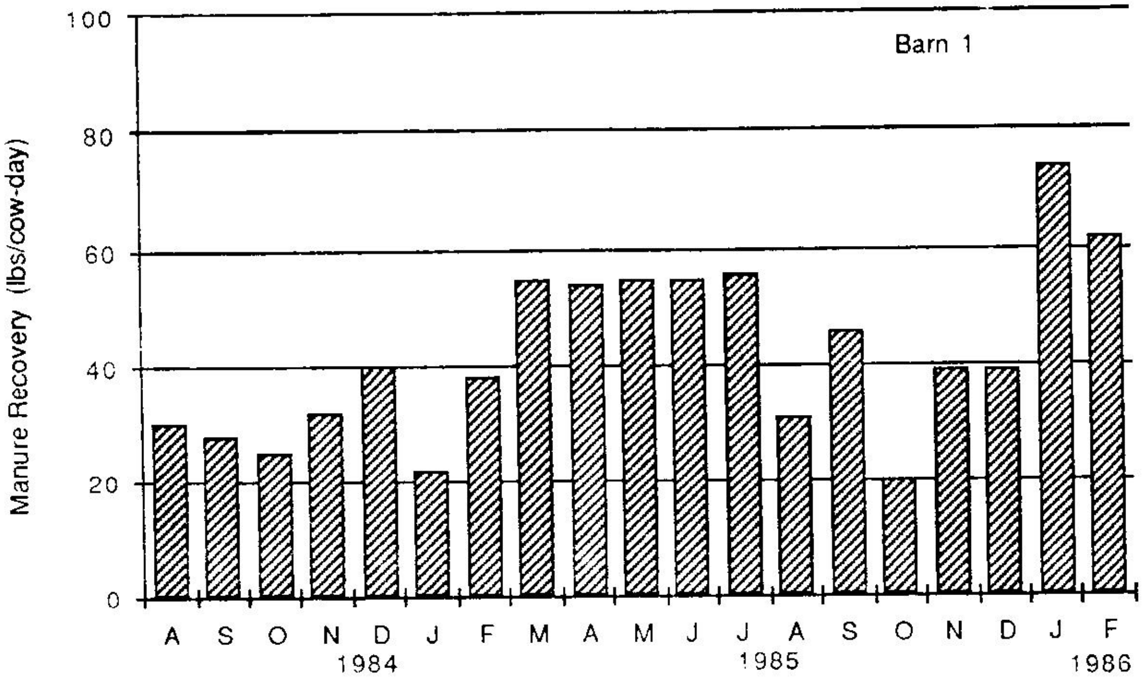


Figure 27. Average monthly manure recovery for loafing barn 1.

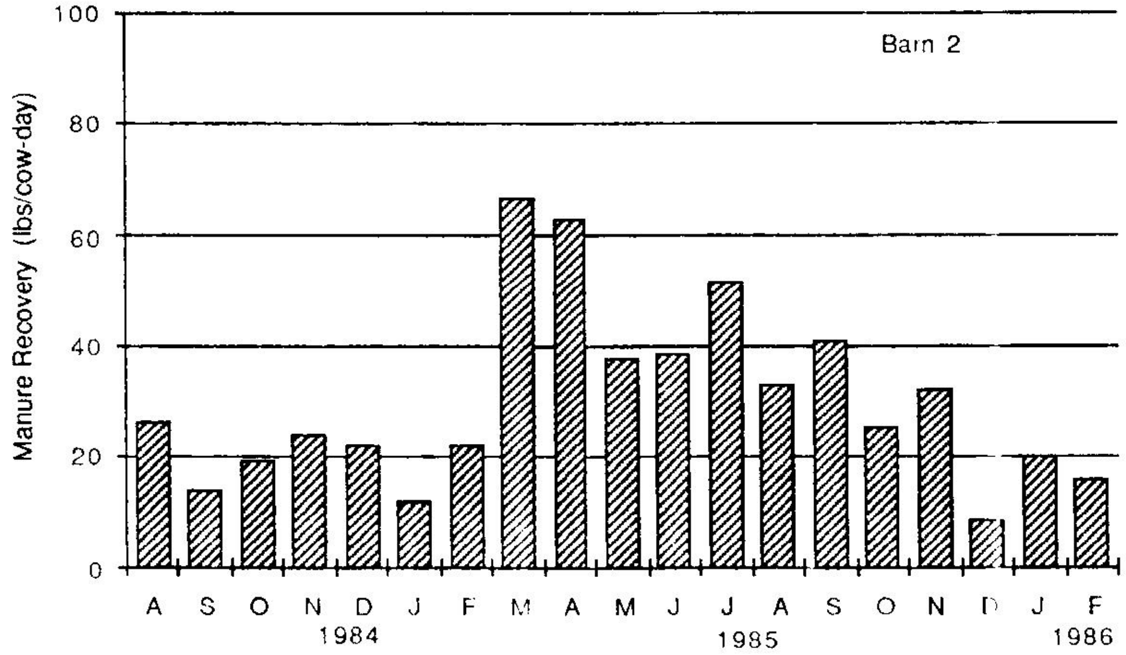


Figure 28. Average monthly manure recovery for loafing barn 2.

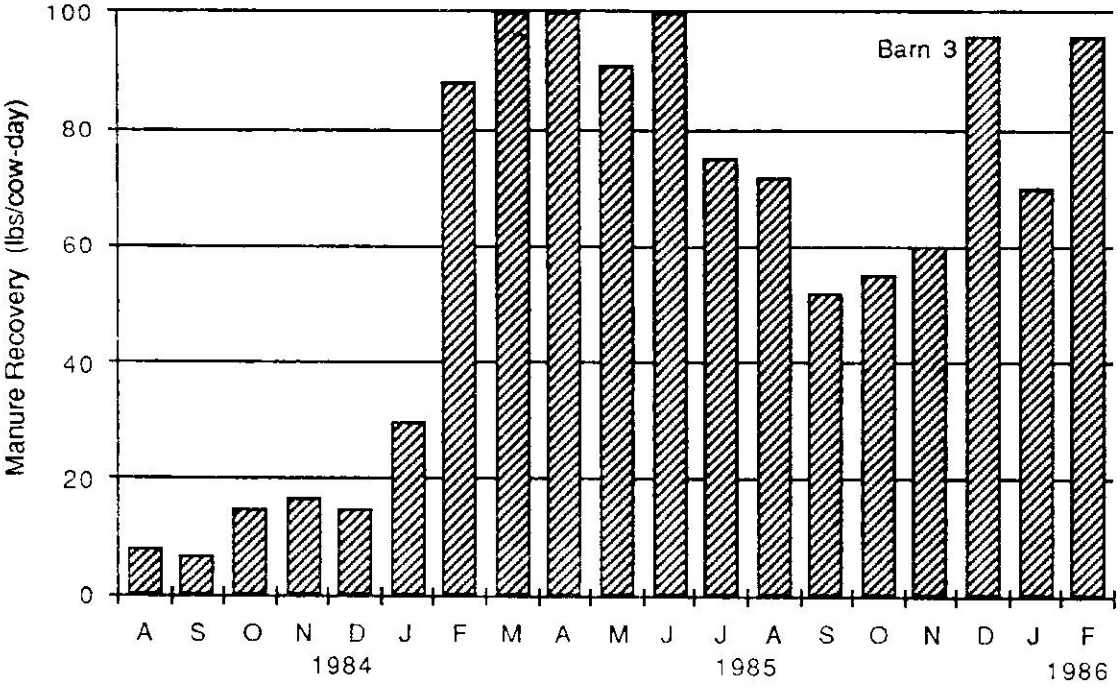


Figure 29. Average monthly manure recovery for loafing barn 3.

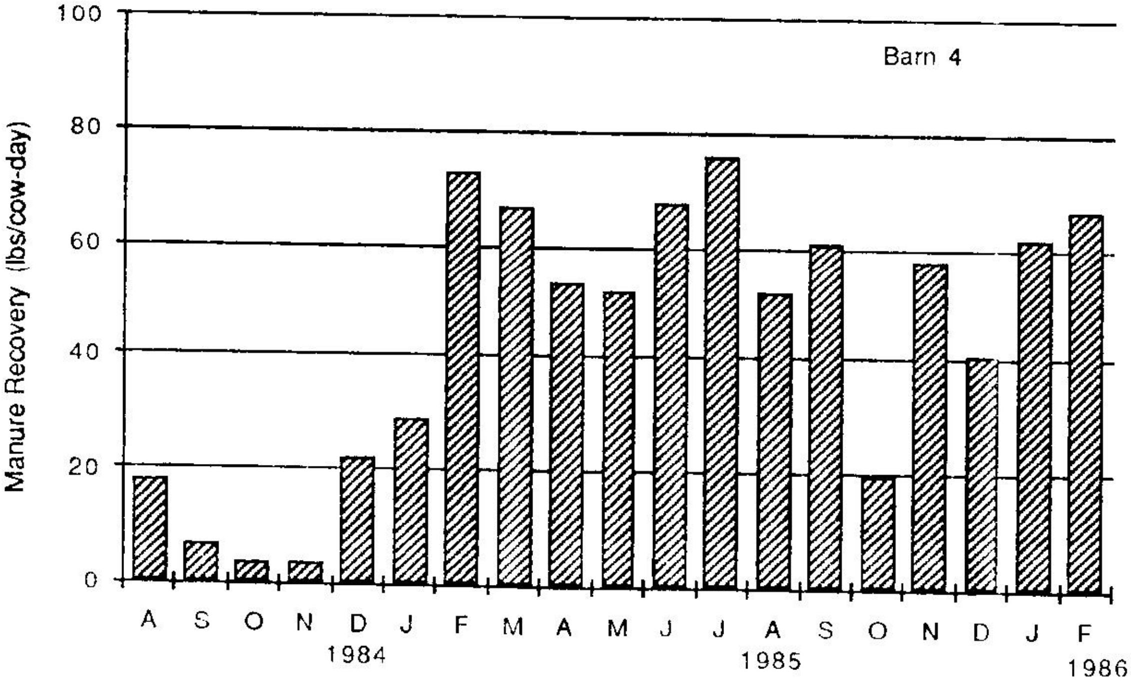


Figure 30. Average monthly manure recovery for loafing barn 4.

1. The cows were not confined to the paved loafing barns. The intent was for cows to be confined to the paved loafing barns most of the day and then allowed on the dirt areas for 2 to 4 hr. This schedule was not followed, and cows moved freely between the pavement and the dirt areas.
2. The loafing barns were not scraped regularly. As discussed above, scraping of the paved barns was not a daily procedure at the cutset of the project. For the project to be successful, farm procedures had to be modified so that personnel and equipment would be available to scrape the barns daily.
3. In loafing barns 3 and 4, cows were fed forage material from hay racks. If the hay racks were parked on the pavement, forage became mixed with the manure, and most of the manure had to be discarded. If the racks were parked off the pavement, cows spent little time on the pavement, and there was no manure to collect. Hay racks were used for these two groups because the farm owner considered the existing feed troughs in loafing barns 3 and 4 inadequate.

The first two of these difficulties were related to farm management, so they were discussed with the farm owner. To eliminate the need for using hay racks, feed troughs were constructed around the perimeter of loafing barns 3 and 4. In addition, free stalls were constructed in barn 3 (Figure 31) so that group of cows could be completely confined.

Construction of the feed troughs and free stalls was completed in January 1985. At the same time, the cows were confined to the paved loafing barns, and manure was collected with more regularity. As a result of these efforts, daily manure recovery increased to between 60 and 70 lb/cow, or 60 to 70%

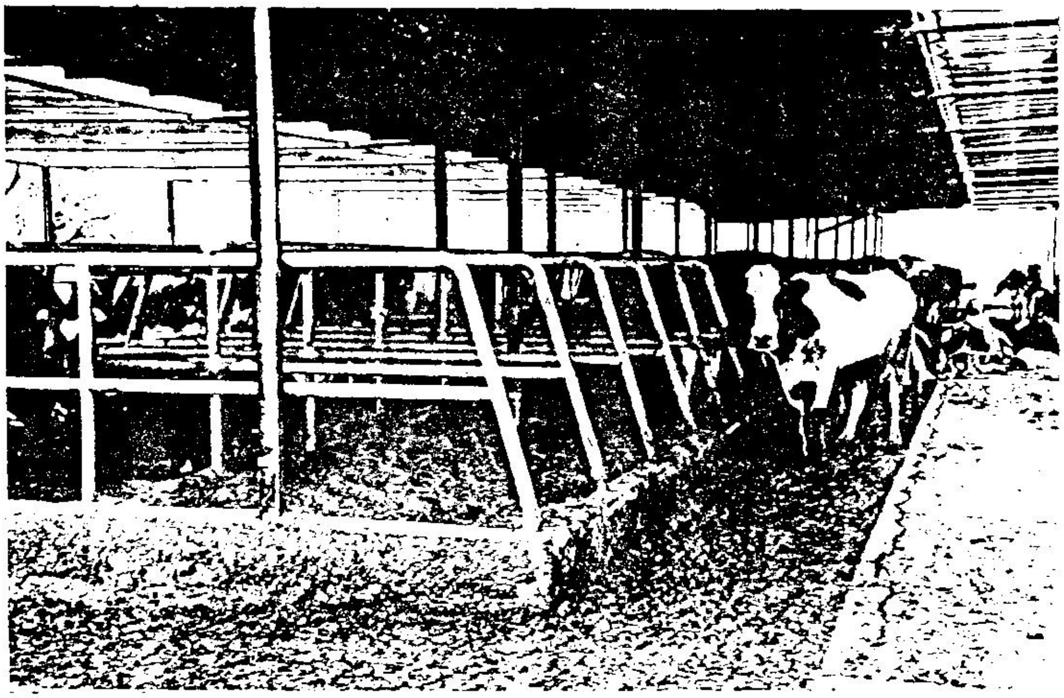


Figure 31. Free stalls constructed in loafing barn 3.

recovery, for the next 6 months. In August 1985, manure recovery dropped below 50% and remained below this level through December 1985. This drop reflected a trend which began in June 1985. During the summer and fall of 1985, loafing barns were still being scraped daily, but, due to equipment failures and a shortage of personnel, manure was not hauled to the mixing sump regularly. When the rains began in August, large amounts of stored manure were washed away each time it rained, especially in October when rainfall was unusually high. By December, the "rainy season" had essentially ended, but little manure was collected during the last half of the month due to the holiday season. In mid-January 1986, a concerted manure collection effort was renewed, and it lasted approximately 4 weeks. Average daily manure recovery during this 4-week period increased to 75 lb/cow. Then, in the last 2 weeks of February, this value declined to 40 lb/cow because regular manure collection ceased.

Maximum manure recovery was from loafing barn 3 (Figure 29), where the free stalls were constructed. The purpose of installing the free stalls was to demonstrate the benefit of free stalls to the farm owner, and the results reflect their value. In addition, loafing barn 3 was easy to scrape, so 100% manure recovery was possible. In loafing barn 4, the cows were confined to the pavement beginning in February 1985. Manure recovery from this loafing barn (Figure 30) was less than that from loafing barn 3 because loafing barn 4 was difficult to scrape effectively. Only during January and February of 1986, did daily manure recovery from loafing barn 1 exceed 55 lb/day (Figure 27). Cows in loafing barn 1 were not always confined to pavement, and this loafing barn was also difficult to scrape effectively. Two factors are mainly responsible for the poor manure recovery in loafing barn 2 (Figure 28). First, cows in this lot were not confined to the pavement for more than 2 to 3 months during the project. Secondly, unlike the other loafing barns which had a single feed trough at the edge of the pavement, loafing barn 2 had two feed troughs in the central portion (Figure 9). As a result, much of the manure from this loafing barn had to be discarded because it had large amounts of long-stem forage mixed in with it. This forage material caused problems throughout the system, so every effort was made to prevent it from entering the system.

Figure 32 shows monthly averages of total manure recovery in gallons per day and normalized to 9% total solids. There are two major reasons why the design volume of 6,400 gal/ day (Table 1) was never attained: (a) the design figure of 75% manure recovery (or 75 lb/cow-day) was never achieved, and (b) the system was designed for 500 cows. There were 400 cows in the four lots when the system was designed; but since the farm owner planned to expand

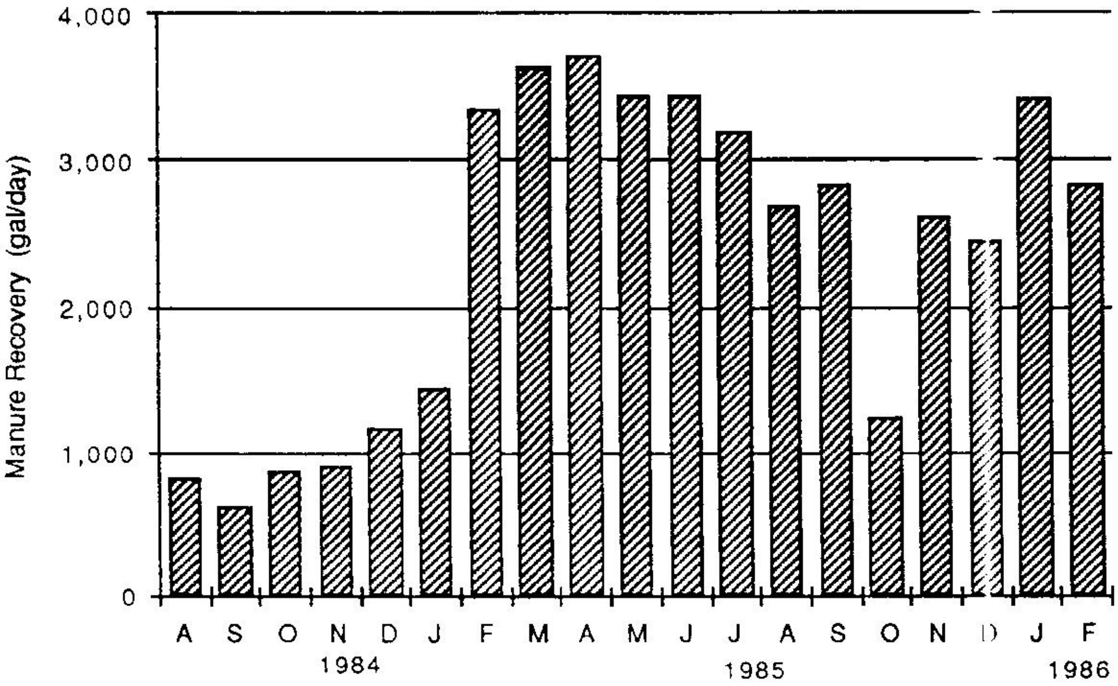


Figure 32. Monthly averages of total daily manure recovery normalized to 9% total solids.

his herd to 500 cows in the near future the latter number was used for the design. When the system was installed and ready to operate, however, the herd size had actually fallen to less than 300 cows (Figure 33). Herd size eventually recovered to 400 cows, but most of the additional cows were placed in a separate dirt enclosure. From February 1985 through the end of the project, the number of cows in the four loafing barns remained between 300 and 330.

Two major difficulties arose as a result of confining cows to the pavement. The original intent of allowing cows off the pavement for 2 to 4 hours daily was never instituted, so cows that were confined were on the pavement all day. No hock injuries were evident, but several cows did exhibit extreme tenderness in their hooves. A second difficulty was that, with the almost daily scraping, the pavement became slippery. As a result, a few cows were lost because their

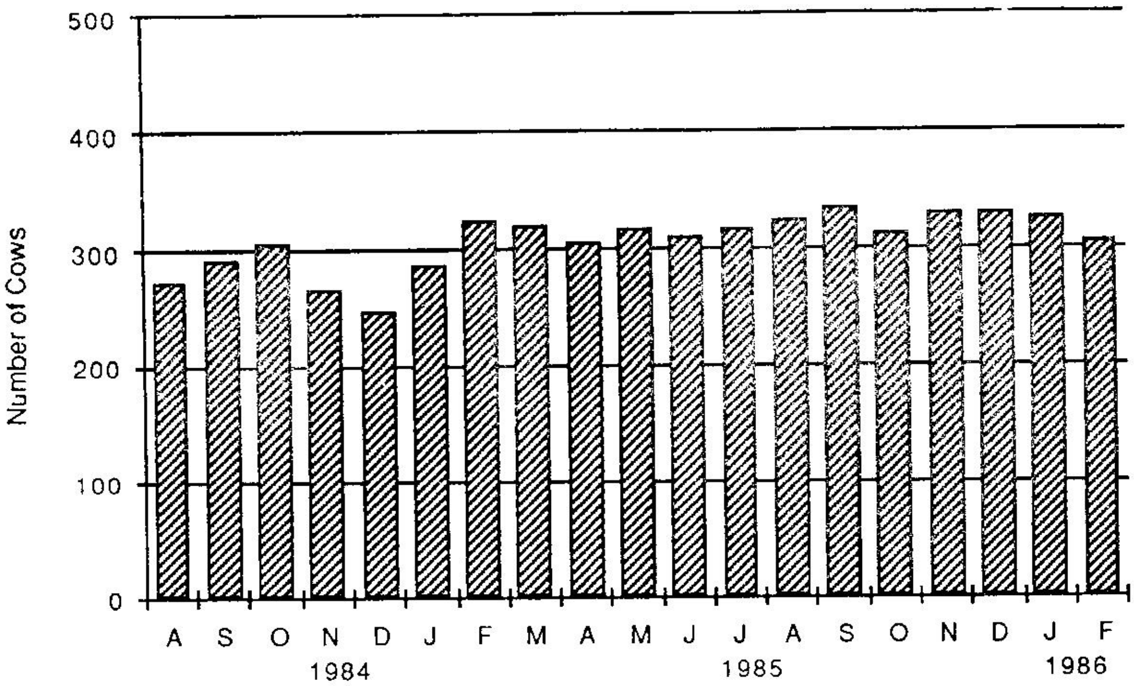


Figure 33. Size of the milking herd on the Río Cañas Dairy Farm.

rear hooves slipped away from their bodies and their pelves were damaged. In retrospect, the floors should have been grooved when they were poured.

4.2.3.2 Manure Preparation. Generally, manure was loaded into the mixing sump in the mid-afternoon. This was convenient since cows were being milked at this time, and there was plenty of dilution water available from the milking parlor. To reduce fluctuations in biogas production, the digesters were loaded twice or, if there was sufficient material, three times daily.

The purpose of the cutter pump in the mixing sump was two-fold: (a) to reduce long-stem forage material, and (b) to homogenize the slurry. It did not reduce long-stem forage material as expected, and this material caused difficulties throughout the system. As far as homogenizing slurry in the mixing sump, the cutter pump proved to be a critical component of the system. Since the loafing barns were open and scraped only once daily, manure often arrived at the mixing sump considerably dehydrated with a total solids content of 25 to 30%. The preferred procedure was to unload the manure slowly with the pump running. When this procedure was followed, it was necessary to run the pump only while unloading. However, if the material was unloaded too quickly or if the pump was not running while the material was unloaded, the material remained in large chunks floating on the surface. These chunks were difficult to break up, even with the pump.

The cutter pump proved highly durable and never failed during the course of the project. Without the cutter pump, the effectiveness of the system would have been severely affected; so careful maintenance and readily available spare parts were important. An alternative to using a cutter pump would have been to transport the manure in an auger-type manure spreader, add dilution water directly to the spreader, and use the auger to mix the manure and water. This was the method used at the Foster Brothers Dairy Farm in Middlebury, Vermont (17).

After the system had been in operation for a short while, it became apparent that, when total solids of slurry in the mixing sump fell below 9%, separation within the slurry occurred and a hard crust formed on the surface. Similar crust formation inside the unmixed digesters would have created serious complications. Therefore, it was decided that total solids of slurry fed to the digesters should be well above the design value of 9%. Slurry with total solids above 13% flowed poorly, so solid content of the feed material was maintained at about 12%. Efforts to develop a field test to determine total solids of material in the mixing sump were not successful due to the presence of long-stem forage material. However, it was not difficult to judge solid content of the slurry by observation.

The mixing sump periodically filled with grit and was cleaned at approximately 4-month intervals. The first grit trap beside the milking parlor (Figure 6) filled in 3 to 4 days, and, aside from digging it out with a shovel, no satisfactory method was found for cleaning it. As a result, the first trap was usually filled with grit, and a channel had to be dug through the grit to allow water to pass to the second grit trap. The second trap took 2 to 3 months to fill.

There was no clogging of the 10-in. piping, but valves which were not used regularly did begin to seize after 10 months of operation. Fortunately, at this point the second digester was ready to be filled, so it was possible to service all valves. Contact surfaces between the shaft and the sleeve were corroded, and there was a considerable accumulation of black "gunk" which was removed by scraping and sanding. The valves were liberally greased and exercised regularly, so they gave no further trouble.

4.2.3.3 Anaerobic Digestion. Prior to loading with manure, the digesters were filled with water and tested to 22 in. of water pressure. There were several small liquid leaks in the seams where the covers joined the sides of the digesters, but once the digesters were filled with manure the seeping soon ceased. Digester 2 was tested and covered with soil soon after construction was completed in the summer of 1984. Because there was not sufficient manure at that time to fill both digesters, digester 1 was not tested until almost a year later, and it was left uncovered all that time. When digester 1 was pressure tested, several gas leaks had developed around the sample tubes where the Vulchem had shrunk and pulled away from the concrete, and superficial cracks had begun to appear in the cover. Once the Vulchem had been replaced, the digester was retested and promptly covered with soil.

The influent pipe for digester 2, the first digester filled, was carefully designed. It extended almost completely across the digester; its end was restricted; and two evenly-spaced holes were cut along its length. The two holes and the end restriction were sized to assure even flow of slurry across the digester. The pipe clogged with grass and had to be backflushed several times during the course of the project. This situation was eventually corrected by draining the digester and cutting the influent pipe off at its mid-point. A simpler design was used for the influent pipe to digester 1. This pipe extended two-thirds of the distance across the digester; it was completely open at the end; and a large hole 6 x 10 in. was cut at its midpoint. While the digester was being filled, a large clump of grass was observed to lodge in the hole, and this influent pipe later clogged. Based on this experience, the best design appears to have been the open-ended pipe extending half-way across the digester.

Figure 34 gives hydraulic retention times for the digesters based on monthly averages of feeding rates. From September 1984 through May 1985 only 1 digester was in use. In June 1985, the second digester was filled and put in operation. As discussed previously, the digesters were sized on the basis of 75% manure recovery from 500 cows. Since actual manure recovery was 40 to 60% from approximately 320 cows, retention times were generally considerably longer than the design retention time of 28 days.

The long retention times did not have an adverse effect on digester performance (Table 4). Total solids reduction and volatile solids reduction were slightly lower than might be expected with such long retention times, but this was probably due to the presence of considerable amounts of long-stem grass mixed with the manure. The pH of the digester effluent was well above seven, and the ratio of volatile solids to alkalinity in the digester effluent was low. Both these factors indicate good digester stability. Methane content of the biogas

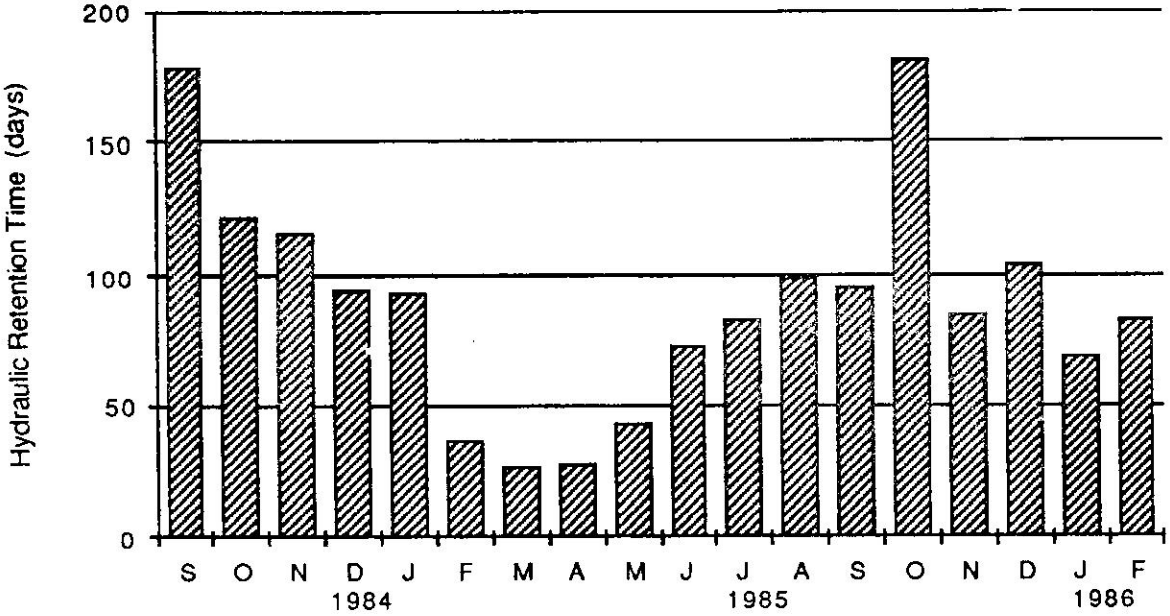


Figure 34. Hydraulic retention time based on monthly averages of digester feed rates.

TABLE 4. DIGESTER PERFORMANCE

| | |
|---|---|
| Total solids reduction | 25% |
| Volatile solids reduction | 30% |
| pH of effluent | 7.3-7.6 |
| Ratio of volatile acids/alkalinity | 0.10-0.13 |
| Percent methane in biogas | 54-58% |
| Cubic feet biogas per pound volatile solids loaded | 6.0 (1 digester)<br>7.0 (2 digesters) |

and conversion in terms of biogas production per pound volatile solids fed to the digester were average, but conversion in terms of biogas production per pound volatile solids destroyed was excellent.

Figure 35 presents the digester efficiency as a function of specific loading rate. Digester efficiency is expressed in terms of daily production of biogas per cubic foot of digester volume. Since cost of the digester is closely related to its volume, this number is a good measure of the digester's cost-effectiveness. Specific loading rate is expressed as pounds of volatile solids fed to the digester daily divided by the digester volume. Normalization of the loading rate to account for digester volume was necessary because some of these data are for one digester and some are for two digesters. Volume of each digester was 11,760 ft$^3$. Digester efficiencies as high as 2.0 are attainable with short retention times (14), and Figure 35 demonstrates that long retention times yield poor digester efficiencies. The two values for digester efficiency which were

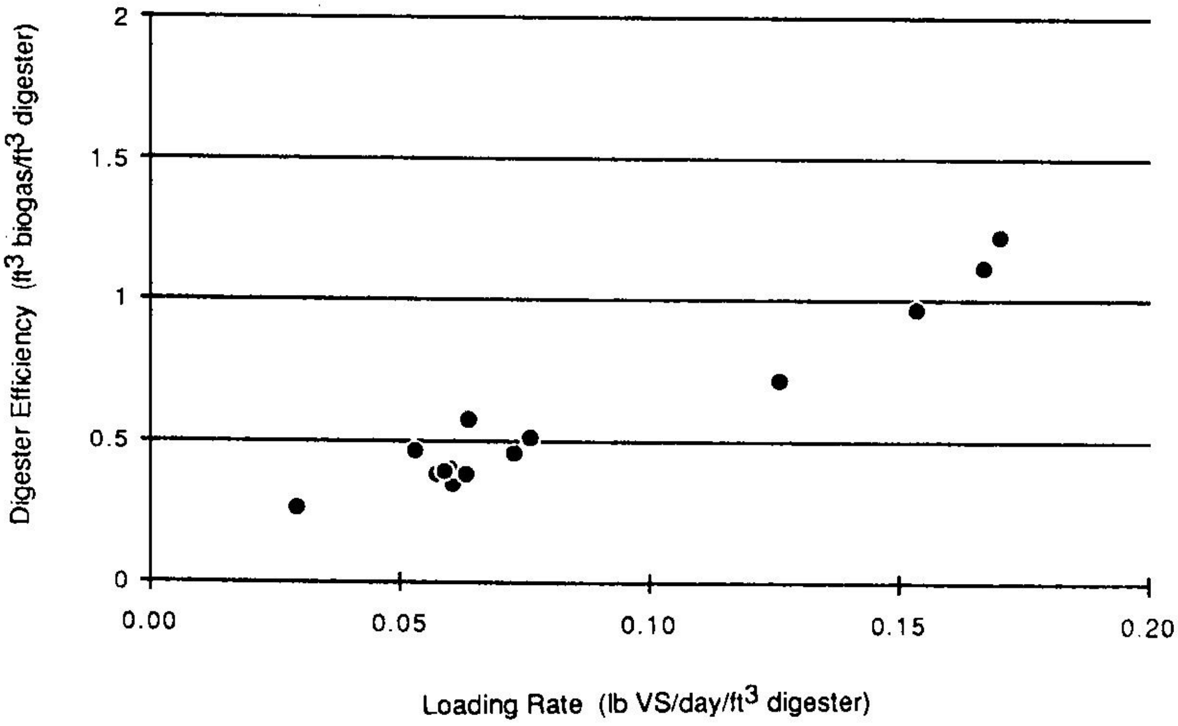


Figure 35. Digester efficiency.

above 1.0 correspond to retention times of 4 weeks. Of the group of points around 0.4 and 0.5, most correspond to retention times of approximately 3 months.

The lack of mixing did not appear to affect the digesters adversely. A floating layer of foam and vegetative material several inches thick formed in the digesters, but it never hardened into a crust which prevented gas from escaping. Several temperature profiles were performed on the digesters, and internal temperatures never varied spatially by more than 2°C. Since the heat exchangers were located on the bottom of the digesters, this uniformity in temperature was probably due to convection.

Figure 36 gives monthly averages for gas production. As would be expected, these data closely reflect the manure recovery data in Figure 26.

4.2.3.4 Electrical Power Production. The engine-generator began running on biogas in early February 1985. Figure 37 shows the relationship between gas production and kilowatt output of the engine-generator. At a sustained rate of less than 400 $ft^3$/hr, no electricity was produced. Beyond this threshold, electrical output increased almost linearly with increased gas production. It is evident from Figure 36 that gas production was minimal for the engine-generator which was purchased. In addition, the numbers in Figure 36 are averages, whereas those in Figure 37 refer to sustained rates of gas production. Gas production fluctuated considerably with digester loading (Figure 38). For this reason, it was preferable to load the digesters with small quantities several times a day rather than loading the day's collection all at one time.

During periods of good system management, gas production was adequate to significantly reduce the farm's electrical costs (Figure 39, Table 5). From February through May 1985, the engine-generator ran only 43% of the

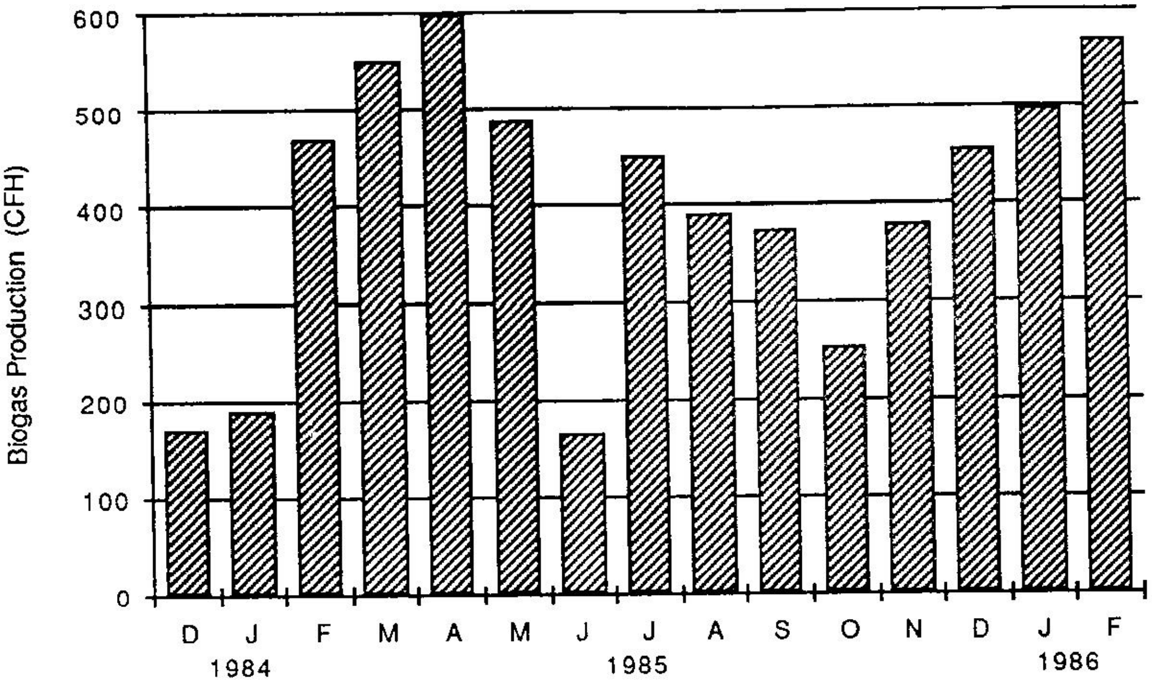


Figure 36. Monthly averages of biogas production.

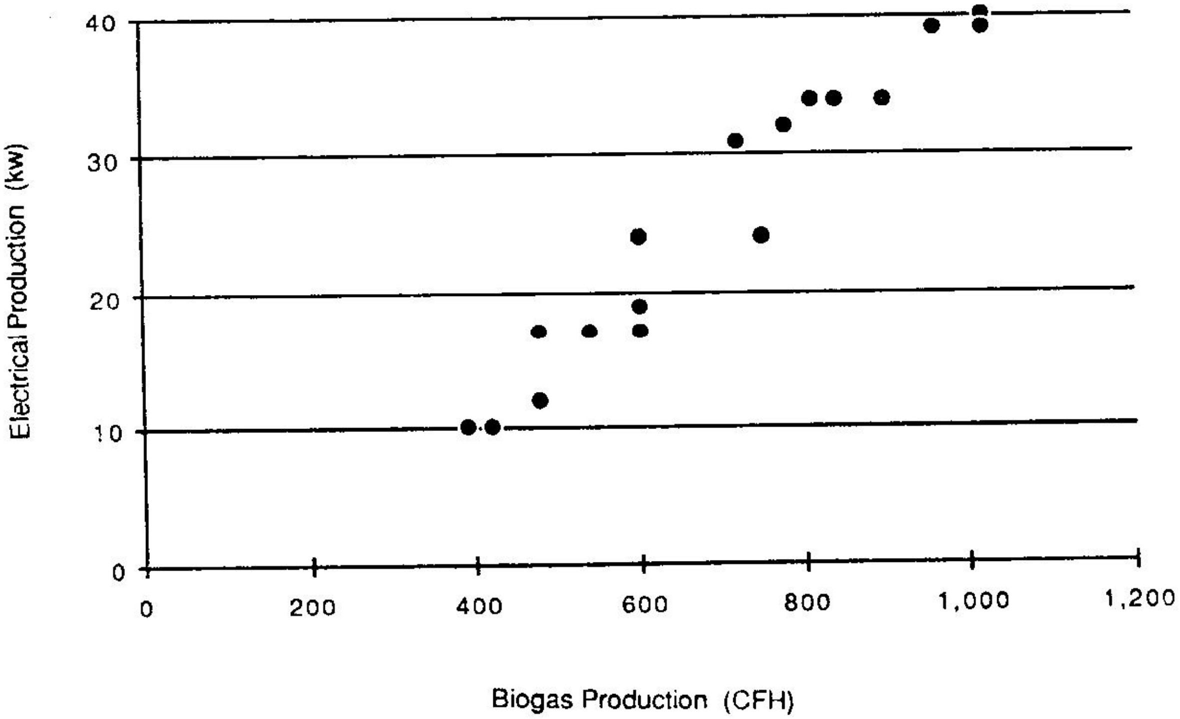


Figure 37. Electrical production by the engine-generator versus biogas production. Below 400 cfh no electricity was produced.

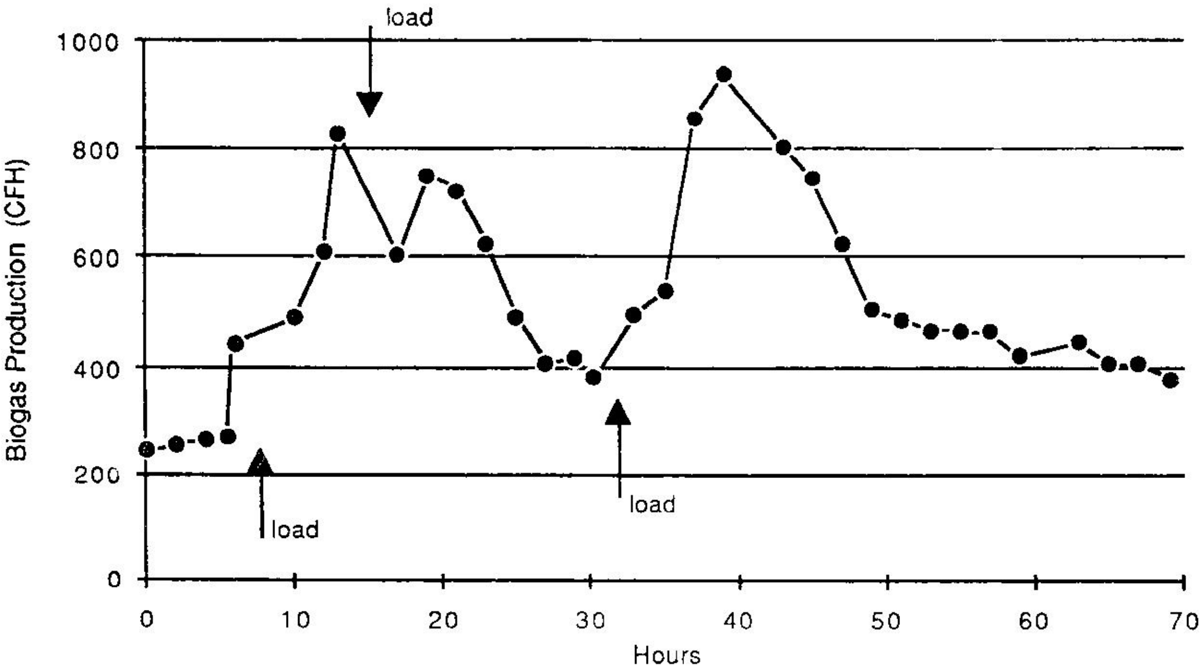


Figure 38. Effect of digester loading on biogas production.

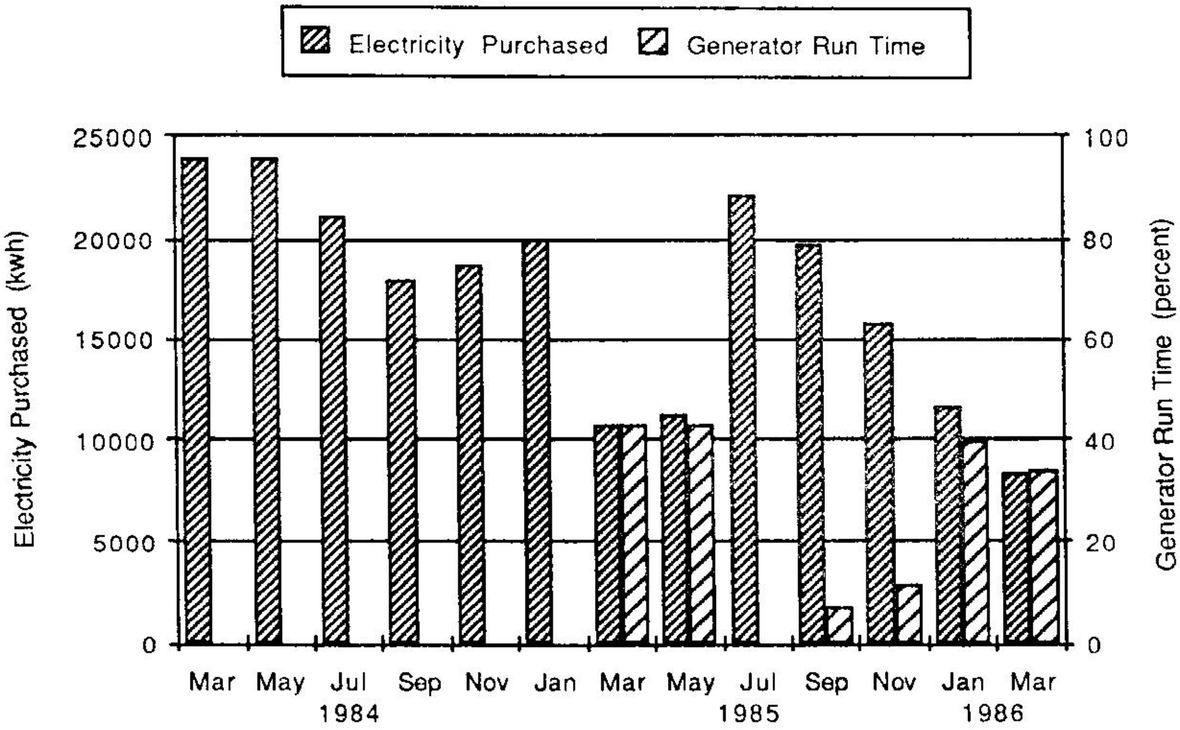


Figure 39. Electricity purchased by the farm plotted beside the number of hours the engine-generator was run. The engine-generator was started in February 1985.

## TABLE 5. ELECTRICAL CONSUMPTION AT THE RIO CAÑAS FARM

| Billing Date | Consumption (kwh) | Cost |
|---|---|---|
| 01/02/80 | 27,260 | $ 2,327 |
| 03/03/80 | 26,210 | 2,236 |
| 05/01/80 | 23,890 | 2,035 |
| 07/02/80 | 27,170 | 2,295 |
| 09/02/80 | 26,170 | 2,325 |
| 10/30/80 | 22,940 | 2,150 |
| 12/30/80 | 23,250 | 2,532 |
| No data * | | |
| 03/23/84 | 23,960 | 2,825 |
| 05/23/84 | 23,960 | 2,891 |
| 07/23/84 | 21,190 | 2,545 |
| 09/21/84 | 17,960 | 2,144 |
| 11/23/84 | 18,720 | 2,191 |
| 01/22/85 | 20,040 | 2,281 |
| 03/21/85 ** | 10,760 | 1,274 |
| 05/22/85 | 11,230 | 1,319 |
| 07/23/85 | 22,170 | 2,446 |
| 09/23/85 | 19,710 | 2,071 |
| 11/22/85 | 15,840 | 1,683 |
| 10/22/86 | 11,630 | 1,202 |
| 03/21/86 | 8,400 | 863 |

* During 1981, 1982 and 1983, the electrical meter was not functioning properly.

** The project engine-generator began producing electricity in February 1985.

time due to minor problems with the engine-generator; yet electricity purchased by the farm over this 4-month period was reduced by approximately 50%. In mid-May, the engine-generator caught fire and was not repaired until July. From July through November, there was not sufficient biogas to run the engine-generator continuously. During these months, the digesters were not fed regularly, so gas production was sporadic and generally below the critical level of 400 to 450 $ft^3/hr$. In late November, a concerted manure recovery effort was renewed, and the engine-generator was restarted. Use of the engine-generator during the last 4 months of the project increased to 37%. and this resulted in a considerable reduction in the amount of electricity purchased by the farm. The engine-generator was running well by this time, but it was not run more often because farm personnel were sometimes not available to operate the system.

Because the engine-generator was oversized, system management was critical. If the engine-generator had been properly sized, a flexible feeding schedule could have been maintained. However, with the oversized engine-generator frequent and regular loading of the digesters was essential. Three different modes of operation are discussed below which illustrate this point:

1. From November 20, 1985 to December 6, 1985 (16 days), manure was collected daily, and the digesters were loaded two or three times a day. Average gas production over this period was 650 $ft^3/hr$, and the engine-generator ran the whole time at an estimated average output of 20 to 25 kW. The farm produced 2,300 kWh more than it consumed.
2. From January 21, 1986 to February 20, 1986 (30 days), the system was operated only on Monday through Friday; but on those days manure was collected regularly and the digesters were fed two or three times daily. Average gas production was 670 $ft^3/hr$, and the engine-generator ran 62% of the time with an average output of 29 kW. The system produced 13,000 kWh, 420 kWh more than it consumed.

3. From February 20, 1986 to March 7, 1986 (15 days), manure was collected only six times. Average gas production fell to 400 $ft^3/hr$, and the engine-generator ran only 15% of the time with an average output of 19 kW. The system produced only 1,000 kWh, and the farm had to purchase an additional 4,300 kWh.

Difficulties encountered with the engine-generator *are described in* Appendix I; however one situation will be discussed here. In March 1985, the liquid-solid separator was installed behind the generator room. Ducting was installed between the engine radiator and the hole in the back wall of the generator room to prevent dust from entering the room. Following this installation, the engine-generator frequently shut down automatically, especially at night, and the warning light came on indicating high water temperature or low water level. This occurred in the midst of several other minor difficulties with the engine-generator, so it was not immediately realized that, with the installation of the radiator ducting, ventilation in the room was no longer adequate to cool the engine. Three measures were taken to improve ventilation of the generator room:

1. A 14-in. ceiling extractor was installed over the engine-generator.
2. Between each of the ceiling beams, 4-in. holes were drilled in the facing boards.
3. Eighteen inches of iron grill were fastened to the bottom of the garage door (Figure 40).

Samples of engine oil were removed regularly and analyzed by Spectron Caribe, Inc., which managed the maintenance program for the engine. The type engine oil used was Castrol RX Super 40. When the oil was changed, both the engine oil filter and the bypass filter element were also changed. The first two oil changes were performed according to the manufacturer's instructions when the engine had 150 hours and again at 450 hours. Oil analyses during this period showed no abnormalities. The next oil change followed the engine fire (see Appendix II) which occurred when the engine had 1240 hours. No abnormalities had been noted up to that point. Spectron recommended an additional oil change at 1300 hours to help clean out the engine. At the end of the project, the engine had a total of 2540 hours, and it had run 1240 hours since the last oil change. Oil analyses at that point were still normal.

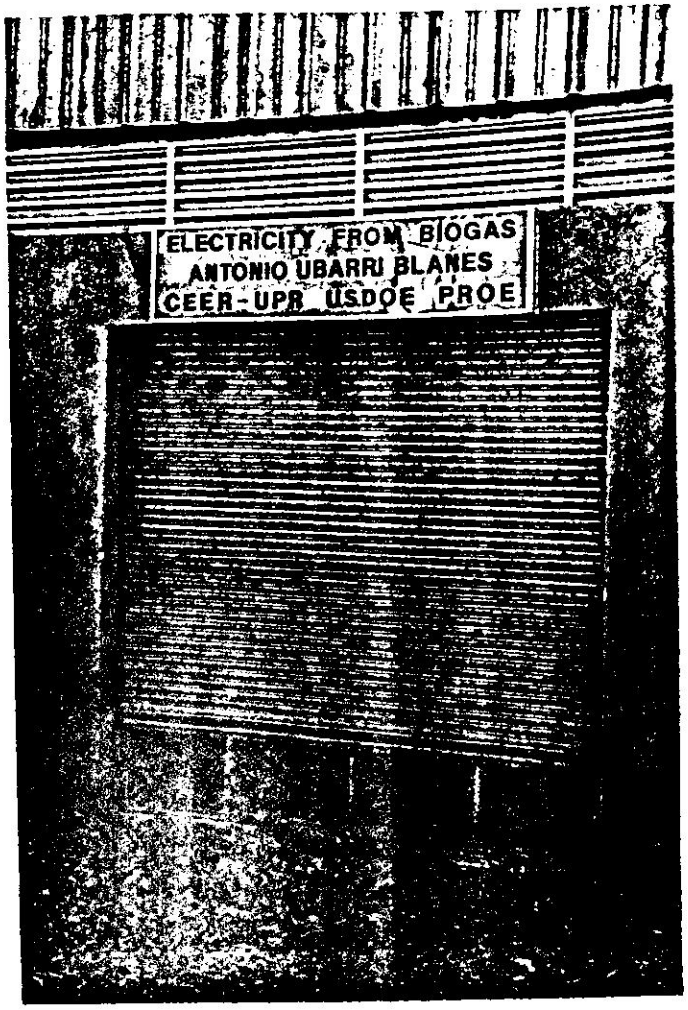


Figure 40. Iron grill fastened to the bottom of the generator-room door.

## 4.3 Farm Waste Management

### 4.3.1 Design

The two main sources of farm waste on the Río Cañas Dairy Farm were raw manure from the four loafing barns and wash water from the milking parlor. Wash water from the milking parlor contained manure and biodegradable detergents.

Figure 41 presents the major components of the waste handling subsystem of the project. Raw manure was collected from the four loafing barns, transported to the mixing sump where it was diluted and homogenized, and then fed to two anaerobic digesters. Effluent from the digesters flowed to a liquid-solid separator. The solid fraction from the separator was composted and either used as bedding material for free stalls or marketed as soil conditioner. The liquid fraction passed to a storage pond for eventual land application to forage crops. Wash water from the milking parlor was used, as needed, to dilute raw manure in the mixing sump. Excess wash water flowed directly to the storage pond.

The anaerobic digesters were an important component of the Farm Waste Management subsystem as well as the Anaerobic Digestion and Electrical Production subsystem. Organic wastes are stabilized by the same bacterial degradation process which produces biogas (9). Under mesophilic conditions, anaerobic digestion destroys between 30 to 50% of the volatile organic material in cattle manure (18).

Digester effluent flowed through a 6-in., underground pipe to the concrete separator well located in the separator building (Figure 42). Elevation of the top of the well was 1 ft above maximum liquid level in the digester overflow sumps,

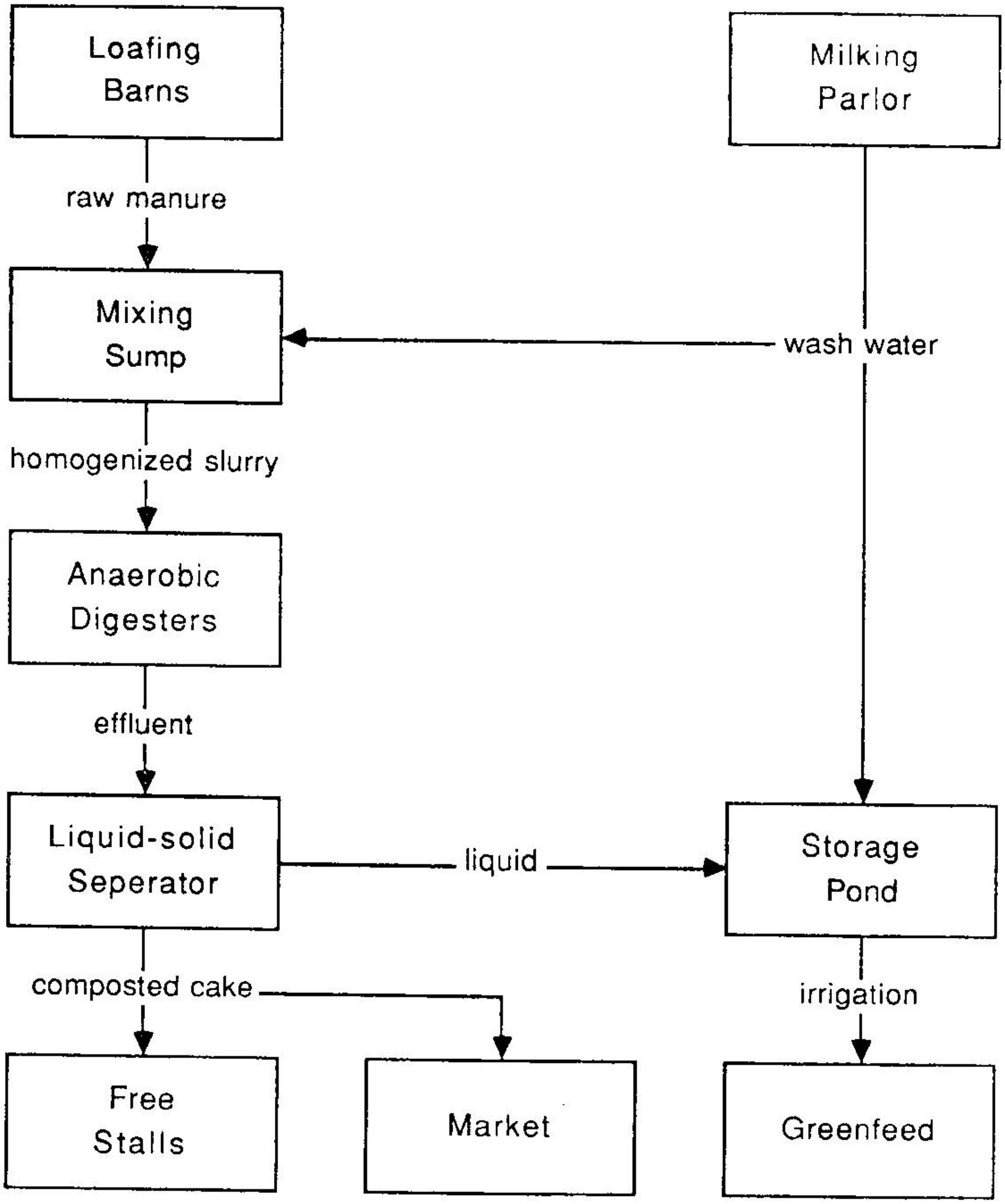
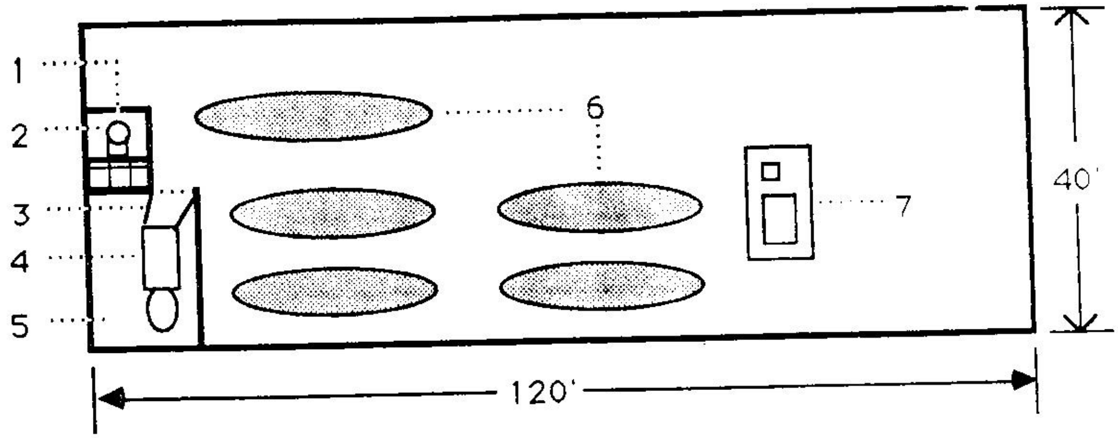


Figure 41. Major components of the Farm Waste Management subsystem.



1 Separator well
2 Liquid-solid separator
3 Radiator ducting
4 Engine-generator
5 Generator soom
6 Composting separator cake
7 Bagging machinery

Figure 42. Diagram of the separator building.

and inside dimensions of the well were 4 x 5.5 ft and 9 ft deep. Total storage capacity for digester effluent, including the two digester overflow sumps, the piping, and the well was approximately 7,000 gal. The well was accessed by a 2 x 4-ft opening in the top which was covered by a removable iron grill (Figure 43).

The liquid-solid separator was mounted on top of the concrete separator well in the separator building (Figure 44). Three types of liquid-solid separators were considered: a drum press, a screen separator coupled to an auger press, and a centrifugal separator. Based on considerations of manufacturer specifications, equipment cost, and conversations with farmers who had experience with the three types of equipment, a DeLaval Lisep (a centrifugal separator manufactured by Alfa-Laval, Inc., Part No. 8304030-81) was purchased. A 3.2 horsepower, submersible Flygt cutter pump (Model 3085.181, Type FP) was chosen to feed the separator. This brand of submersible cutter pump has been used extensively for manure handling and was highly

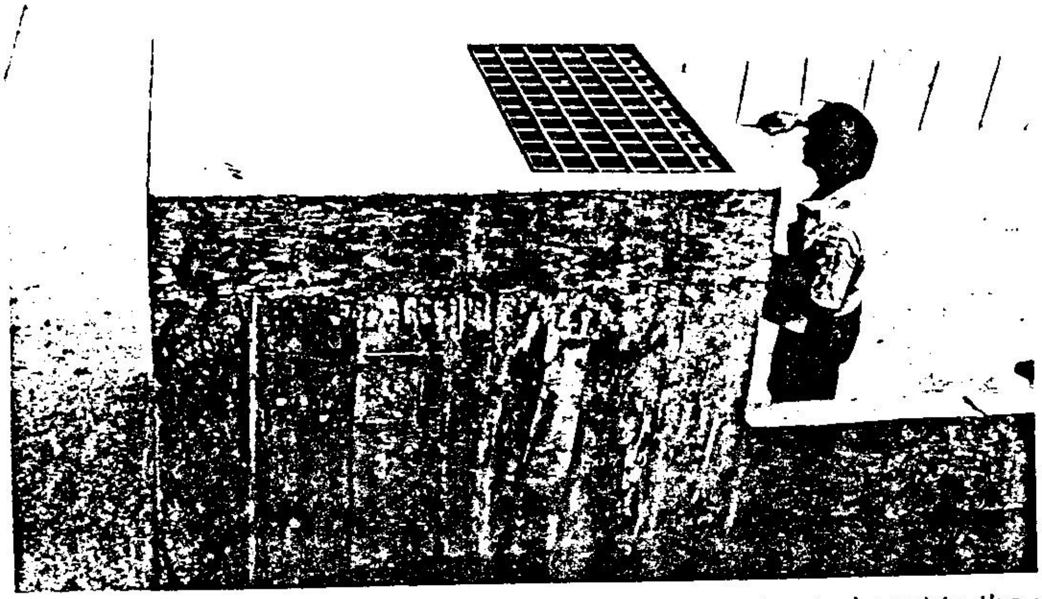


Figure 43. Separator well. Generator room was constructed next to the well.

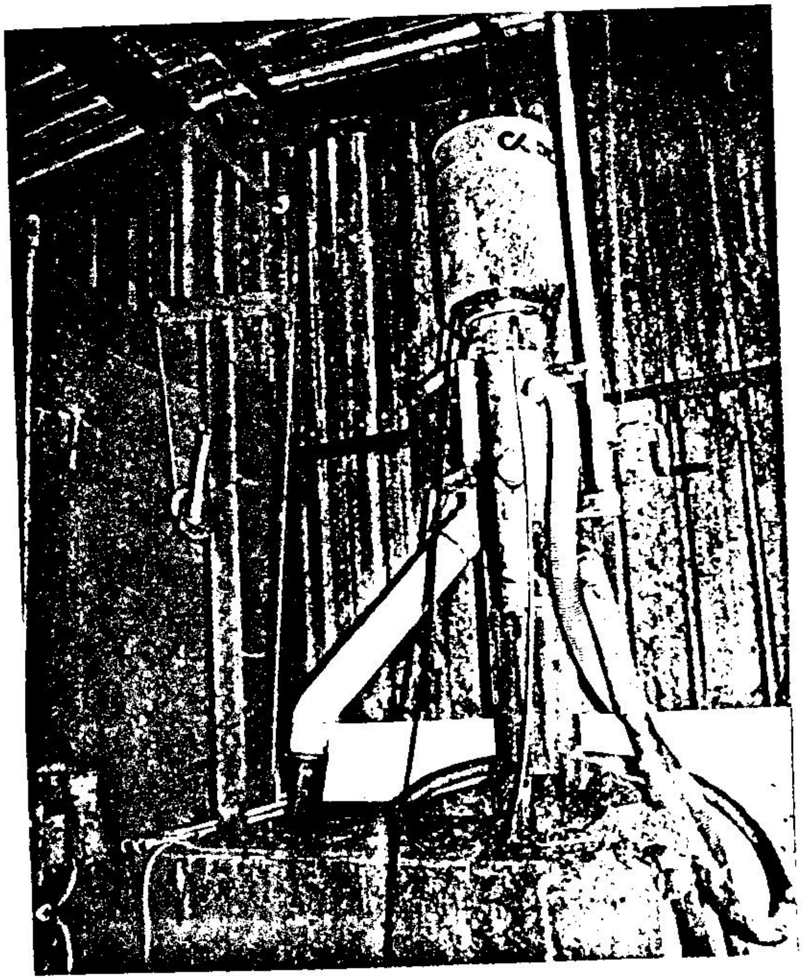


Figure 44. Liquid-solid separator mounted on separator well.

recommended. According to manufacturer's specifications, feed rate of the separator should be less than 40 gal/min, while output from the cutter pump was approximately 150 gal/min. To reduce flow from the cutter pump, a bypass was added to the feed hose of the separator (Figure 45) so that some slurry was diverted back into the well.

The separator building was an open-sided, steel structure 40 x 120 ft and 15 ft high (Figure 23). The first 50 ft of the end where the separator was located was paved with concrete since the range of the Lisep was between 40 to 50 ft. The unpaved portion was used for additional composting space, bagging equipment for the separator cake, and for farm equipment storage.

The solid fraction (or cake) from the separator accumulated beside the separator and was turned regularly until fully composted. Composted material was primarily for use as bedding material in the free stalls in loafing barn 3, and excess material was to be marketed as a soil conditioner. The liquid fraction from the separator had a high nutrient value, so it flowed to a storage pond for

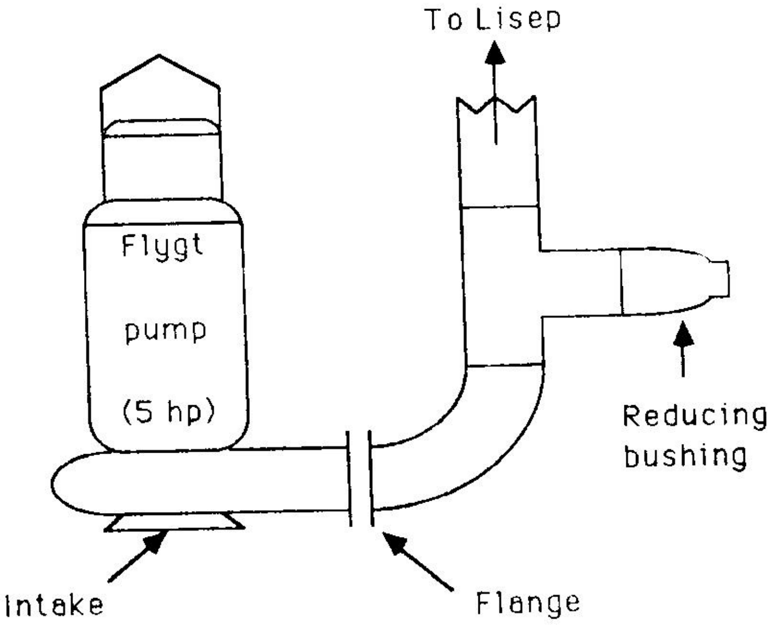


Figure 45. Bypass on feed hose to liquid-solid separator

eventual application to greenfeed crops.

The storage pond was designed in cooperation with personnel from the U.S. Soil Conservation Service office in Juana Díaz, Puerto Rico. It was designed to provide 30 days storage for a maximum daily input of 10,000 gal. Bottom dimensions were 50 x 80 ft with a side slope of 2:1. The pond was 8 ft deep with 1 ft of freeboard. A 1-ft blanket layer of clay was laid down on the bottom and on the sides to prevent seepage.

### 4.3.2 Operation and Performance

Anaerobic digestion reduced volatile solids of the manure by 30% (Table 4). Considering the long retention times within the digesters, this value is low, but this may be a result of the large amount of forage material mixed in with the manure. Biological Oxygen Demand of the manure was reduced by 75%, and Chemical Oxygen Demand was reduced by 50%.

The 6-in. pipe between the digester overflow sumps and the separator well was subject to clogging. Flow through this pipe was slow, and the pipe was always full of liquid. As a result, grit collected in the pipe and eventually filled it. Removing grit from this pipe was very difficult. The fact that grit passed through the mixing sump and the digesters to settle out in this pipe and in the separator well was not expected.

Performance of the separator did not match manufacturer specifications. According to the manufacturer, the separator should recover 40 to 50% of the solids from slurry with 6 to 9% solid content; cake should have a moisture content of 65% solids; and the liquid fraction should have a moisture content of approximately 95%. During the course of the project, the separator was used more than 500 hours. Input to the separator was generally between 9 to 10%

solids; cake was consistently about 75% moisture content, and solid content of the liquid fraction averaged 12% less than the input. This means that only approximately 20% of the solids in the digester effluent were being recovered by the separator. Low solids recovery by the separator may have been due to the large amount of long-stem forage material which passed through the system. Clogging of the feed worm was common, and both the impeller and the paddle had to be replaced after only 400 hours. The manufacturer sells a macerator for the separator, but this accessory was not purchased because it was incorrectly assumed that the two cutter pumps in the system would chop the long-stem material. During one brief period, cows were fed sorghum silage instead of long-stem grasses. A sample toward the end of this period showed an increase to 30% solids recovery by the separator.

Cake from the separator accumulated in piles 4 to 5 ft high, and then the piles were turned (Figure 46). Subsequently, they were turned weekly until temperatures inside the piles fell to near ambient temperature and the material turned dark, indicating the end of the composting process. During composting, temperatures within the piles generally remained at between 140°F and 150°F, and the composting process required from 5 to 6 weeks. The farm owner rarely applied bedding to the free stalls because he considered this process too time-consuming. Most of the composted cake was ground, placed in 9-qt (5.5-lb) plastic bags, and marketed as soil conditioner at 50 cents per bag wholesale. It was necessary to perforate the plastic bags, or the material began to smell badly after a few weeks.

The storage pond was completed in April 1984, before the anaerobic digesters were functional. Upon completion, the pond was filled with wash water from the milking parlor, and this liquid was pumped onto the forage crops using a pump which belonged to the farm. The following June the pump failed,

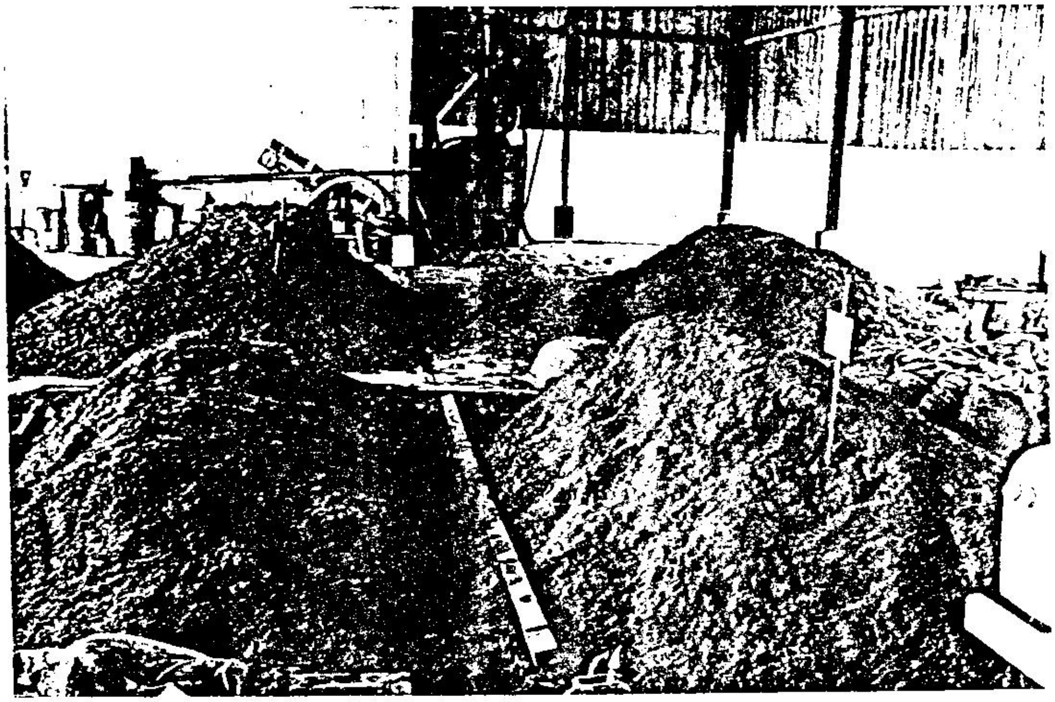


Figure 46. Composting cake from the liquid-solid separator.

and the pond's contents began overflowing into a nearby stream. The design of the Farm Waste Management subsystem had been approved by the Puerto Rico Environmental Quality Board. If it had been fully implemented, the Río Cañas Dairy Farm would have been the first dairy farm in Puerto Rico to dispose of its animal waste in a manner consistent with environmental regulations. The pump was never repaired, so the Farm Waste Management subsystem was never fully operational.

## 4.4 Greenfeed Production and Usage

### 4.4.1 Design

In the mainland United States, dairy farmers usually grow most of the feed for their dairy cattle, but Puerto Rican dairy farmers are largely dependent on external sources of feed. This is partially due to poor utilization of land resources , but equally important is the high cost of chemical fertilizers. A dairy farmer, however, has an excellent natural fertilizer at his disposal in the form of cow manure. Dairy farms in Puerto Rico with sufficient tillable land and adequate water supplies should be able to use dairy manure as a nutrient source for growing grasses as a partial replacement for purchased hay and grain.

The climate in Puerto Rico is well suited for growing forage grasses throughout the year. Night temperatures, which are the rate-limiting factor for growth of tropical grasses, are sufficiently high to ensure year-round productivity of forage grasses. On the Río Cañas Dairy Farm, cows were fed a mixture of commercial grain concentrate, roughage extenders, and forage material. Operating costs could be considerably reduced if the dairy grew at least part of its own forage material. Adequate land resources were available, but annual rainfall for the area averaged only 33 in., and approximately 50% of this precipitation fell during the "rainy season" months of August, September, and October. Pan evaporation rates for the area averaged 87 in. per year. Therefore, irrigation was essential for the development of a greenfeed subsystem. Fortunately, the Costa Sur irrigation canal, which was constructed of concrete approximately 70 years ago to supply water to area sugar cane crops, crossed the farm, and irrigation water could be drawn from this canal. An overhead portable sprinkler system (Rainbird 150 with three-quarter-inch nozzles) and several thousand feet of irrigation pipe was available for use in the greenfeed subsystem.

The grasses selected for the greenfeed subsystem were napier grass (Pennisetum purpureum, merker variety, hybrid PI 7350), several varieties of sorghum (Sordan 70A, Sordan 79, Sudax, Trudan, and Graze-All), and buffel grass (Pennisetum ciliare, nueces variety). Merker is very labor-intensive to plant (it is propagated from stem cuttings rather than from seeds), but a stand of Merker can sustain cutting every 5 to 6 weeks for a period of 5 to 8 years. Merker 7350 is superior to Common Merker with respect to growth potential, feed value, disease resistance, and tolerance to arid conditions. It is also more tolerant of repeated mowing with flail-type mowers (19). Both Merker and sorghum respond well to nitrogen fertilization and irrigation, and they have been used extensively as cattle forages (20,21). Sorghum has the advantage that it is more palatable to cattle. Buffel grass is a hardy perennial which can survive in the absence of fertilizers and irrigation if necessary, although crop yields of unmanaged stands are greatly reduced.

### 4.2.2 Operation and Performance

Planting of the greenfeed crops began in the summer of 1982. The initial plantings were not successful because they were not irrigated properly, so the crops were replanted in December 1982. In May 1983, the greenfeed subsystem was well established, and operation of this subsystem was turned over to the the farm owner. Initially, the greenfeed had been fertilized with cow manure, but in 1983 the farm owner used chemical fertilizers because their application required less labor. In April 1984, the farm owner began pumping from the storage pond onto the greenfeed crops with noticeably beneficial results. Two months later, the pump failed, and he reverted to using chemical fertilizers on the greenfeed crops.

Land preparation for all crops was basically the same. First, a mold board plow was passed over the fields in two directions followed by a disc. The fields were then rotavated, fertilized, and cross rotavated. For planting Merker, furrows were cut 14 in. apart and 8 in. deep, and stem cuttings were placed three-abreast in the furrows.

Germination of the first planting of Merker was poor and yielded a stand of low density. The difficulty in germination resulted from the need for stem cuttings to lie in warm, moist soil in order to stimulate germination. The arid soil at the Río Cañas Dairy Farm, although irrigated, apparently could not retain sufficient moisture to stimulate germination in most cuttings. In fact, due to high evaporation rates and high soil porosity, the planted stem cuttings appeared to be losing moisture to the ambient soil. This problem was effectively countered by pretreating fresh stem cuttings before they were planted. This pretreatment consisted of holding cuttings in piles of several tons each, covering them with a thick layer of leaf material to retard desiccation, and watering them frequently. After 3 days, most stem cuttings showed signs of root-growth initiation and bud swelling and expansion. Stem cuttings planted in this condition and irrigated immediately gave almost 100% establishment. To avoid the added labor of unloading and reloading stem cuttings, this pretreatment could be administered while cuttings were in the truck.

A seed drill was used to plant sorghum, and approximately 60 lb/acre of seed were applied. Buffel grass was seeded with a fertilizer spreader at a seed density of 20 lb/acre. When chemical fertilizer was used, it was applied at an annual rate of 2,000 lb/acre. Pesticides were used as needed against army worms, but no herbicides were necessary.

Initially, a flail chopper was used for harvesting, but this was later replaced with a forage harvester which did not fray the ends of the stalks so badly. Both Merker and sorghum were harvested at intervals of 44 to 60 days, while buffel grass was cut at intervals of 35 to 45 days. The supply of irrigation water proved to be unreliable so crop yields varied considerably. When adequate water was available, yields for Merker and sorghum were 15-20 green tons per acre per cutting, and yields for buffel grass were approximately 10 green tons per acre per cutting. The dry matter content of buffel grass is higher than that of Merker or sorghum. so these yields are comparable.

After operation of the greenfeed subsystem was turned over to the farm owner, no attempt was made to influence his choice of crops. When the project ended, 5 acres of Merker (the size of the original planting) remained, and there were 90 acres of buffel grass. With these crops, the farm was able to supply approximately 40% of its forage needs. Yields were reduced because the supply of irrigation water was sporadic due to storm damage to the country's irrigation system. The last planting of sorghum died in the summer of 1984 when there was a severe drought and irrigation water was not available. The Merker and the buffel grass both survived the drought. When cows were fed sorghum, there was a noticeable increase in milk production of 2 to 5%. In spite of this, the farm owner did not continue growing sorghum, partly because sorghum could not survive without irrigation and partly because, unlike the other two crops, sorghum is an annual.

The farm owner was impressed with the hardiness and yields of the Merker grass, but no additional Merker was planted because it was very demanding and time-consuming to plant. The buffel grass proved extremely hardy and a very easy crop to grow and manage. It had the additional advantage that, unlike Merker, it could be used either as greenfeed or dried and baled. Greenfeed was convenient because storage facilities were not needed, but when it rained greenfeed could not be cut and the cows had to be fed hay. This is not desirable because consistency in diet is important for cows. The farm owner decided to feed a mixture of hay with greenfeed, so that the cows could adjust in either direction in a minimum amount of time.

# 5.0 ENERGY AND ECONOMIC ANALYSIS

For effective operation of an anaerobic digester system, efficient and regular manure collection is essential. As described in Section 3.1, disposal of animal wastes on the Río Cañas Dairy Farm had not previously been a major concern, and cow manure often accumulated in the lots for several months before it was removed. It is doubtful that the dairy farm could have operated in this manner if environmental regulations had been strictly enforced since organic and nutrient loading of the stream which ran through the farm probably exceeded allowable limits. With the installation and operation of an anaerobic digester system on the Río Cañas Dairy Farm, both energy consumption and costs for manure collection increased considerably.

Two sets of energy and economic analyses were conducted with the UPR-EIDF project. First, energy and economic analyses were performed on the system as it was implemented. A second set of analyses was performed assuming that the manure collection component was already active and that no additional energy consumption or cost was required for manure collection. This is a reasonable assumption since manure is considered a valuable resource on many U.S. dairy farms, where and it is recovered and used to fertilize crops.

The second set of analyses also included corrections for the sizing of system components. As discussed in Section 4.2.3.3, the system was designed to handle manure from 500 cows, but actual herd size was only about 320 cows; so the mixing sump, digesters, and engine-generator were all oversized. In the second set of analyses, these components were properly sized for a dairy herd of 320 cows. The greenfeed subsystem was not included in the second set of analyses because it was not closely tied to the other two subsystems and because it was not affected by the above-mentioned changes.

Assumptions used for these analyses were:

1. Manure recovery was 75% of the total amount available.
2. The system operated 350 days a year.
3. Electrical output from the engine-generator was constant, at 25 kW.
4. Electricity from the public utility cost $0.12/kWh, and they purchased electricity at $0.05/kWh.
5. There were no seasonal variations in electrical consumption on the farm.
6. All solids recovered from the digester effluent by the liquid-solid separator were either used on the farm or sold.
7. Fifty percent of the nitrogen in the liquid fraction from the liquid-solid separator was available to the forage crops. This would provide approximately 45% of the nitrogen needed to fertilize 90 acres.
8. All forage for the cows was provided by the greenfeed subsystem. This assumes an annual yield of 11 dry tons per acre from 90 acres, which is well below maximum yields obtained.

## 5.1 First Analysis

### 5.1.1 Energy

The first energy analysis indicated a savings of 1,705 million Btu/year for the anaerobic digestion and farm waste management subsystems, and a savings of 7,718 million Btu/year for the entire system (Table 6). Major energy consumers in the system were the tractors for manure collection and the greenfeed subsystem, the pump in the mixing sump, the separator with feeder

TABLE 6. FIRST ENERGY ANALYSIS

| Subsystem | Energy Rate (unit/hr) | Energy Value (Btu/unit) | Efficiency | Use (hr/yr) | Savings (MBtu/yr) |
|---|---|---|---|---|---|
| Anaerobic Digestion | | | | | |
| Manure Collection (tractors) | -3.0 gal/hr | 35,000 Btu/gal | 25% | 1,400 | -588 |
| Manure Preparation (pump) | -14.9 kW | 3,413 Btu/kWh | 33% | 1,050 | -160 |
| Electrical Power (gen-set) | 25.0 kW | 3,413 Btu/kWh | 33% | 8,400 | 2,152 |
| Farm Waste Management | | | | | |
| Separator and Pump | -6.1 kW | 3,413 Btu/kWh | 33% | 700 | -44 |
| Separator Liquid | 1.5 lb N/hr | 28,000 Btu/lb N | 100% | 8,400 | 345 |
| | | | | Subtotal (MBtu/yr) | 1,705 |
| Greenfeed | | | | | |
| Fertilizer | -1.7 lb N/hr | 28,000 Btu/lb N | 100% | 8,400 | -411 |
| Irrigation Pump | -3.0 gal/hr | 35,000 Btu/gal | 25% | 700 | -294 |
| Tractors | -3.0 gal/hr | 35,000 Btu/gal | 25% | 2,800 | -1,176 |
| Forage | 235.0 lb/hr | 4,000 Btu/lb | 100% | 8,400 | 7,895 |
| | | | | Net Energy Savings (MBtu/yr) | 7,718 |

pump, and the irrigation pump. Electrical energy was produced by the engine-generator, and additional energy credits were taken for the fertilizer value of the separator liquid and for the greenfeed.

### 5.1.2 Simple Payback

Table 7 is an economic analysis for the project as it was implemented. The first column of numbers is the capital cost for system components, and the remaining columns itemize costs or benefits related to system operation. Energy rates for electricity produced by the engine-generator were based on the relative hourly consumption rates presented in Figure 21. With a constant production of 25 kW, the farm would have purchased only 16 kWh/day of electricity, and it would have sold 203 kWh/day to the electrical utility. Maintenance costs for individual items were calculated as a percentage of their capital costs, and labor costs were assumed to be $6/hr.

Capital cost for the anaerobic digestion subsystem was $293,700, and this subsystem had a net operational deficit of $5,965 per year. When the anaerobic digestion subsystem and the farm waste management subsystem were considered together, the capital cost was $334,400, and there was a net annual operational profit of $17,091. This yielded a simple payback period for these two subsystems of almost 20 years. Simple payback for all three subsystems together was 8.2 years.

TABLE 7. FIRST COST ANALYSIS

| | | Operational Costs or Benefits | | | | | |
|---|---|---|---|---|---|---|---|
| Subsystem | Capital Cost | Energy Rate (unit/hr) | Unit Value ($/unit) | Use (hr/yr) | Main-tenance ($/yr) | Labor ($/yr) | Total ($/yr) |
| Anaerobic Digestion | | | | | | | |
| Manure Collection | | | | | | | |
| Loafing Barns | $67,200 | | | | $672 | $96 | -$768 |
| Equipment | $21,000 | -3.0 gal/hr | $1.03 /gal | 1,400 | $1,050 | $8,880 | -$14,256 |
| Manure Preparation | | | | | | | |
| Mixing Sump & Piping | $44,000 | | | | $440 | $96 | -$536 |
| Pump | $8,700 | -14.9 kW | $0.12 /kWh | 1,050 | $435 | $240 | -$2,552 |
| Anaerobic Digesters | $97,800 | | | | $978 | $96 | -$1,074 |
| Electrical Power | | | | | | | |
| Generator Room | $13,000 | | | | $130 | $96 | -$226 |
| Engine-Generator | $42,000 | | | | $6,300 | $480 | -$6,780 |
| Power Used | | 16.5 kW | $0.12 /kWh | 8,400 | | | $16,674 |
| Power Sold | | 8.5 kW | $0.05 /kWh | 8,400 | | | $3,553 |
| Farm Waste Management | | | | | | | |
| Building & Piping | $18,700 | | | | $187 | $96 | -$283 |
| Separator & Pump | $12,500 | -6.1 kW | $0.12 /kWh | 700 | $625 | $240 | -$1,377 |
| Separator Cake | | 37.5 lb/hr | $0.05 /lb | 8,400 | | $3,150 | $12,600 |
| Separator Liquid | | 1.5 lb N/hr | $1.00 /lb N | 8,400 | | | $12,308 |
| Storage Pond | $9,500 | | | | $95 | $96 | -$191 |
| Subtotal | $334,400 | | | | | Subtotal | $17,091 |
| Greenfeed | | | | | | | |
| Fertilizer | | -1.7 lb N/hr | $1.00 /lb N | 8,400 | | | -$14,692 |
| Irrigation Equipment | $95,000 | -3.0 gal/hr | $1.03 /gal | 700 | $1,900 | $480 | -$4,543 |
| Tractors & Equipment | $50,000 | -3.0 gal/hr | $1.03 /gal | 2,800 | $2,500 | $17,280 | -$28,432 |
| Forage Material | | 235.0 lb/hr | $0.05 /lb | 8,400 | | $8,760 | $89,943 |
| Total Capital Costs | $479,400 | | | | Net Operational Benefits | | $59,368 |

## 5.2 Second Analysis

### 5.2.1 Energy

Table 8 presents an energy analysis for the project assuming that no additional energy was required for manure collection. Under this condition, energy savings increased to 2,293 million Btu/yr for the anaerobic digestion and farm waste management subsystems.

### 5.2.2 Simple Payback

When capital and operating costs for manure collection were eliminated and when components were properly sized, economics of the system improved considerably (Table 9). Capital costs for the anaerobic digestion subsystem fell to $152,600, and this subsystem operated at a net profit of $10,288/yr, yielding a simple payback of 14.8 yr. When the anaerobic digestion and farm waste subsystems were linked together, simple payback was 5.8 yr.

## 5.3 Return on Investment

Based on data gathered during the project, an estimate of the return on investment was projected for various herd sizes and for different interest rates. The same assumptions listed in Section 5.0 were used for this analysis along with the following assumptions:

1. Useful lifetime was 20 years for structural components such as the digesters and 10 years for equipment such as the engine-generator.

TABLE 8. SECOND ENERGY ANALYSIS

| Subsystem | Energy Rate (unit/hr) | Energy Value (Btu/unit) | Efficiency | Use (hr/yr) | Savings (MBtu/yr) |
|---|---|---|---|---|---|
| Anaerobic Digestion | | | | | |
| Manure Collection (tractors) | -3.0 gal/hr | 35,000 Btu/gal | 25% | 0 | 0 |
| Manure Preparation (pump) | -14.9 kW | 3,413 Btu/kWh | 33% | 1,050 | -160 |
| Electrical Power (gen-set) | 25.0 kW | 3,413 Btu/kWh | 33% | 8,400 | 2,152 |
| Farm Waste Management | | | | | |
| Separator and Pump | -6.1 kW | 3,413 Btu/kWh | 33% | 700 | -44 |
| Separator Liquid | 1.5 lb N/hr | 28,000 Btu/lb N | 100% | 8,400 | 345 |
| | | | | Net Energy Savings (MBtu/yr) | 2,293 |

TABLE 9. SECOND COST ANALYSIS

| | | Operational Costs or Benefits | | | | | |
|---|---|---|---|---|---|---|---|
| Subsystem | Capital Cost | Energy Rate (unit/hr) | Unit Value ($/unit) | Use (hr/yr) | Main-tenance ($/yr) | Labor ($/yr) | Total ($/yr) |
| Anaerobic Digestion | | | | | | | |
| Manure Collection | | | | | | | |
| Loafing Barns | $0 | | | | $0 | $0 | $0 |
| Equipment | $0 | -3.0 gal/hr | $1.03 /gal | 0 | $0 | $0 | $0 |
| Manure Preparation | | | | | | | |
| Mixing Sump & Piping | $34,100 | | | | $341 | $96 | -$437 |
| Pump | $8,700 | -14.9 kW | $0.12 /kWh | 1,050 | $435 | $240 | -$2,552 |
| Anaerobic Digesters | $59,800 | | | | $598 | $96 | -$694 |
| Electrical Power | | | | | | | |
| Generator Room | $13,000 | | | | $130 | $96 | -$226 |
| Engine-Generator | $37,000 | | | | $5,550 | $480 | -$6,030 |
| Power Used | | 16.5 kW | $0.12 /kWh | 8,400 | | | $16,674 |
| Power Sold | | 8.5 kW | $0.05 /kWh | 8,400 | | | $3,553 |
| Farm Waste Management | | | | | | | |
| Building & Piping | $18,700 | | | | $187 | $96 | -$283 |
| Separator & Pump | $12,500 | -6.1 kW | $0.12 /kWh | 700 | $625 | $240 | -$1,377 |
| Separator Cake | | 37.5 lb/hr | $0.05 /lb | 8,400 | | $3,150 | $12,600 |
| Separator Liquid | | 1.5 lb N/hr | $1.00 /lb N | 8,400 | | | $12,308 |
| Storage Pond | $9,500 | | | | $95 | $96 | -$191 |
| Total Capital Costs | $193,300 | | | | Net Operational Benefits | | $33,344 |

2. The manure collection component was already active.
3. Digesters were designed for a 28-day hydraulic retention time.
4. Daily gas production was 40 $ft^3$ biogas per cow.
5. Electricity was generated at a rate of 1 kW/500 $ft^3$ biogas per day.
6. Daily farm electrical demand was 1.3 kWh per cow.
7. Inflation rate was zero, so all dollar values are in 1984 dollars.

Table 10 presents the return on investment for herd sizes of 300, 400, 500, and 600 cows. Interest rates of 10, 12, and 14% were used. Annual costs refer to operational costs, as in Tables 7 and 9, plus loan payments. Annual benefits are the same as those in Table 7 and 9.

The economy-of-scale is readily apparent in these analyses. For several components - such as piping, valves, pumps, separator, electrical wiring, and the generator room - capital costs were not affected by herd size. For other items - such as the engine-generator - increases in capital costs were relatively small as herd size increased. These data also suggest that installing anaerobic digester systems on farms with fewer than 500 cows is only marginally profitable.

## 6.0 OPERATIONAL FACTORS

As with any other farm operation, careful maintenance is critical to the successful implementation of the EIDF system. This section discusses system components where regular monitoring and maintenance were required. When applicable, estimates of the amount of time involved are included.

## TABLE 10. RETURN ON INVESTMENT

| 300 cows | Interest Rate | | |
|---|---|---|---|
| | 10% | 12% | 14% |
| Annual Cost | $38,900 | $41,800 | 44,900 |
| Annual Benefit | $44,800 | $44,800 | $44,800 |
| Net Profit | $5,900 | $3,000 | ($100) |
| Return | 15% | 7% | 0% |

| 400 cows | Interest Rate | | |
|---|---|---|---|
| | 10% | 12% | 14% |
| Annual Cost | $42,700 | $46,000 | $49,400 |
| Annual Benefit | $53,300 | $53,300 | $53,300 |
| Net Profit | $10,600 | $7,300 | $3,900 |
| Return | 25% | 16% | 8% |

| 500 cows | Interest Rate | | |
|---|---|---|---|
| | 10% | 12% | 14% |
| Annual Cost | $46,200 | $49,800 | $53,500 |
| Annual Benefit | $61,800 | $61,800 | $61,800 |
| Net Profit | $15,600 | $12,000 | $8,300 |
| Return | 34% | 24% | 16% |

| 600 cows | Interest Rate | | |
|---|---|---|---|
| | 10% | 12% | 14% |
| Annual Cost | $49,500 | $53,400 | $57,400 |
| Annual Benefit | $70,300 | $70,300 | $70,300 |
| Net Profit | $20,800 | $16,900 | $12,900 |
| Return | 42% | 32% | 22% |

## 6.1 Waste Water System

There are two grit traps located adjacent to the milking parlor and a third grit trap in the bypass line between the milking parlor and the storage pond. These grit traps should be checked twice a week and cleaned as necessary. Cleaning a grit trap requires approximately one-half day.

## 6.2 Manure Collection

Cattle manure is corrosive so careful maintenance of the manure spreader is essential. The spreader should be hosed after every use. Axles and moving bed should be greased once a week, and the moving bed should be adjusted as needed.

## 6.3 Mixing Sump

### 6.3.1 Grit

The mixing sump is the primary place for separating grit from the manure. The sump is divided into two parts by a retaining wall 20 in. high. The left side of the mixing sump, the side nearest the milking parlor, is the area that collects the most grit. This area should be checked weekly by inserting a long rod into the center and measuring the depth of the grit. When the grit reaches a depth of about 18 in., the sump should be drained and cleaned. A back-hoe equipped tractor is the most effective method for cleaning the mixing sump. Two people can perform the task in one-half day.

### 6.3.2 Cutter Pump (20 hp)

6.3.2.1 Service. The pump in the mixing sump is a key component in the manure handling system and should receive regular maintenance. The "Installation, Care and Maintenance" manual, number 3152.180 gives complete instructions on the care and maintenance of this pump and should be read and understood by the system operator.

6.3.2.2 Electrical Cable. It is important to pay attention to the electrical cable on the pump. This cable should never be allowed too much slack as it could be caught and destroyed in the impeller blade. The cable should also be inspected regularly for chafing. A break in the insulation could cause an electrical short circuit, thereby causing damage to the pump or injury to farm personnel.

6.3.2.3 Winch Stand and Cable. The cable should be checked weekly for signs of corrosion. The cable connector is connected to the pump by means of a 1-in. shackle. This shackle should be rinsed and inspected for corrosion whenever the pump is raised.

## 6.4 Digesters

### 6.4.1 Valves

Because of the difference in design of the input manifolds for the two digesters, the inlet valve for digester 2 should be partially closed. To prevent freezing, these valves should be exercised weekly. When not in use, valve handles should be removed to prevent tampering.

### 6.4.2 Grit

As the digesters fill with sand, their usable volume is reduced, and heat exchanger pipes become covered. Every few months, the digesters should be checked for grit accumulation. When grit reaches the first tier of heat exchanger pipes, they should be cleaned.

### 6.4.3 Overflow Pipes

A crust tends to form on the digester overflow pipes. These pipes should be cleaned weekly.

### 6.4.4 Gas Collection Pipes

The gas collection pipes should be inspected frequently for corrosion, particularly at the joints.

## 6.5 Gas Handling Unit

### 6.5.1 Valves

Two ball valves lead into the gas handling unit. These should be kept open but exercised regularly. A single gate valve controls gas flow from the gas handling unit to the engine-generator. This valve should also be exercised regularly to ensure that it does not freeze.

### 6.5.2 Gas Meters

The oil in these two meters is normally clear and should be checked weekly for color. When the oil becomes opaque, it should be changed in accordance with the instructions found in the "Roots Meters Manual # IRM-LM-MA revision 4/83." This manual is included in the back of the "Meter Beater Manual."

### 6.5.3 Condensate Drains

There are four condensate drains located at the meter end of the gas handling unit. These drains should be drained every morning to remove any condensate from the system. They should be kept closed at all other times.

### 6.5.4 Gas Filter

This filter should be changed in accordance with instructions in Section XXI of the "Meter Beater Manual."

## 6.6 Electrical Generation System

### 6.6.1 Engine

Before operating the engine a thorough reading of Section X entitled "Understanding the System" of the "Meter Beater Manual" is essential. It is especially important to check engine oil daily and add new oil when necessary. There are several maintenance schedules with this system. Section VI of the "Meter Beater Manual" gives a list of items to be checked at predetermined intervals. Section VII gives instructions for the coolant. Section XIV gives instructions for tuning the engine for either propane or biogas. TrackerTrol adjustments are also covered in Section XIV. Pages 15 and 16 of the "Operation Guide: 3304 Natural Gas Engine" have a complete maintenance schedule which should be followed carefully. Electrolyte level of the battery should be checked at least once weekly. Distilled water should be added whenever the level drops below the base of the filler tubes.

### 6.6.2 Heat Recovery System

All hose connections should be checked regularly for leaks. There are two Fill-Trol pressure regulators and air purgers located on top of the generator room. These should be checked for leaks at least once a month.

### 6.6.3 Generator

The instructions found in the "Marathon Electric Standard Induction Motors Manual" included in the back of the "Meter Beater Manual" gives specific instructions on how to grease the motor bearings. These instructions should be followed closely as the amount of grease in the bearings is very important. This procedure should be done once every 6 months. The air duct screens should be cleaned at the same time.

## 6.7 Solid Separation System

### 6.7.1 Liquid-Solid Separator

Although there is very little maintenance to be performed on the separator, it should be cleaned after each use. While the separator is in operation, it should be checked for clogging twice hourly since stems and string that get into the system clog the intake of the separator. When this happens, the separator must be turned off, and the trash removed before restarting the system. Increased water content of the cake suggests impeller wear, and reduced range indicates that the paddle has become deformed.

### 6.7.2 Cutter Pump (5 hp)

The "Installation, Care and Maintenance" manual number 3085.181 included in the "Meter Beater Manual" gives complete instructions on the care and maintenance of this pump and should be read and understood by the system operator. It is important to pay attention to the electrical cable on the pump. This cable should never be allowed too much slack as it could be caught in the impeller blade and destroyed. The cable should be inspected regularly for chafing.

### 6.7.3 Pump Output Hose

This hose should be checked regularly for any loosening of the connections and for signs of chafing. A bypass has been installed in the output hose, and this should be checked periodically for clogging.

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# APPENDIX I

## Eliminated Subsystems

## Eliminated Subsystems

Included in the original design for the project were two subsystems which were later eliminated. These were the Solar and Wind Power subsystem and the Aquaculture subsystem.

Solar energy was to be used to dry residual solids recovered from the digester effluent and to dry fish from the aquaculture subsystem. Dried products were then to be used as a feed supplement for the dairy cattle. Since the Department of Health would not permit the refeeding of dried residual solids from manure to dairy cattle and since the aquaculture subsystem was eliminated, the solar power component was not necessary.

Wind power was to be used to pump water from the clarification ponds back to storage tanks located beside the mixing sump. Water from the storage tanks could then be added to the mixing sump, as needed, to dilute the raw manure. As discussed on page 23 of this report, adequate dilution water was available from the milking parlor, so wind power was not needed.

The Aquaculture subsystem was to be used to clarify digester effluent. Liquid was to flow to four, one-quarter-acre clarification ponds which contained water hyacinths. Periodically, the hyacinths were to be harvested, chopped, transported to the mixing sump, and blended with manure as a digester feedstock supplement. Partially clarified water would then pass to four additional ponds, also one-quarter acre each, which were stocked with fish (Tilapia). The fish would be harvested periodically, dried, ground, and used as a high-protein feed supplement for the dairy cattle.[1] Several considerations led to the elimination of the aquaculture subsystem:

1. Only a limited amount of flat land was available for planting forage crops on the farm. The farm owner expressed a strong preference for using available flat land for agricultural purposes rather than for the aquaculture subsystem .
2. The economic value of the hyacinths was almost nothing, while harvesting and processing them required a considerable investment in both man-hours and equipment.
3. The digester effluent had a Biological Oxygen Demand (BOD) of 10,000 to 20,000 mg/l. Even after partial clarification by dewatering and the hyacinth ponds, it is doubtful that the BOD would have been reduced enough so that fish could have survived in the water. Therefore, several thousands of gallons of dilution water would have been needed daily to reduce the BOD to an acceptable level in an area where water is a valuable and often limited resource.
4. Evaporation rates for the area were high. Monthly averages for pan evaporation ranged from 5.4 in. in November to 8.8 in. in July, so daily evaporation from an open pond would range from 4,900 to 7,700 gal/acre. Including digester overflow and excess wash water from the milking parlor, estimated daily flow to the ponds would have been approximately 8,000 gal/day.

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[1] Alexander, A. G. "Systems Design and Installation of an Energy Integrated Tropical Dairy Farm," Phase I Supplement and Progress Report, Contract No. DE-FC001-80CS-40376, October 1982.

5. Local prices for fish meal were $0.22/lb. Assuming a yield of 2,000 lb of <u>Tilapia</u> per acre per year, the value of the harvested fish would have been $440/year. The cost of regularly harvesting the pond and processing the fish would have far exceeded this amount.

# APPENDIX II

## Engine Generator

## Engine Generator

During the course of the experiment, several difficulties were encountered with the engine-generator. They are discussed in this Appendix along with the steps taken to correct them.

### Oil Level Sight Glass

Mounted beside the engine was an oil-level sight glass equipped with a sensor which automatically shut the engine off when oil level dropped below a certain level. A pressure-equalizer tube ran from the top of the sight glass and was connected to the engine flywheel housing by a straight fitting. During the first few months of operation, the unit frequently shut down, and a warning light indicated low oil level when, in fact, there was plenty of oil. Oil was splashing into the pressure-equalizer tube, and this situation created a positive pressure in the sight glass forcing the oil level in the sight glass down. The solution was to install a vertically-oriented elbow fitting at the flywheel-housing end of the tube which prevented oil from splashing into the tube.

### Coolant Level Gauge

Beside the coolant reservoir, there was a gauge which indicated the level of the coolant. The gauge was connected to the reservoir by a nylon tube which was not able to withstand the combined heat and pressure to which it was exposed. This tube was replaced by a copper line.

## Magnetic Valve on Biogas Line

Both the biogas and propane gas lines feeding the carburetor were equipped with magnetic valves which were part of the safety-shut-down system. The first three coils installed in the magnetic valve on the biogas line burned out immediately, and no cause could be found. As a result, the valve was disabled for most of the experiment. Toward the end of the project, a fourth coil was installed and gave no trouble.

## Engine Overheating

Following installation of the radiator ducting, the engine overheated several times due to inadequate ventilation of the generator room. A detailed discussion is on page 66 of this report.

## Engine Fire

Control circuits of the engine-generator consisted of a 110-volt AC circuit and a 12-volt DC circuit. The 12-volt DC circuit controlled, among other things, activation of both the cooling fan motor and the safety system. A 12-volt battery powered the DC circuit, and this battery was charged by a battery charger which ran off the AC circuit. Part of the role of the safety system was to protect against engine overheating. If engine oil temperature or engine coolant temperature rose above a predetermined limit, a relay was activated which shut the engine down.

With this design, if the 12-volt DC circuit lost power then both the cooling fan and the safety system were disabled, and this is what happened in May 1985. The sequence of events appears to have been as follows:

1. The battery charger failed, and the battery lost power.
2. As the engine temperature rose, there was not enough power to activate the relay to turn on the cooling fan motor.
3. As the engine temperature continued to rise, there was no power to activate the safety relay which shut the engine off.
4. The extreme engine heat melted the plastic sensing lines for biogas pressure and oil pressure. Biogas began leaking into the room, and oil began leaking onto the hot engine. The oil then ignited.
5. Biogas trapped among the rafters was ignited either by the burning oil or by the explosion of the transformers mounted on the exhaust manifold.

Damage to the engine was limited to the wiring harness, ignition system, and head assembly. An analysis of the engine oil immediately after the fire showed slightly increased viscosity, a three-fold increase in aluminum, and slightly elevated levels of iron, chromium, magnesium, and phosphorus. According to Spectron, the elevated aluminum could have come from either the pistons or the bearings. Since chromium was also elevated, they believed that source of the aluminum was probably the pistons, which did not present a major problem.

Since the unit was still under warranty, Perennial Energy was contacted to see if the damages were covered by warranty. They refused to pay for repairs to the engine, but they did prepare and send an undervoltage relay circuit to prevent a repetition of the situation.