Pilot Plant Demonstration of a Three-Stage Waste Treatment Technology

Final Report

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Preface and Acknowledgements

On December 1998, DGH Engineering Ltd. received funding of $93,000 to evaluate the performance of a Taiwanese manure treatment technology at the pilot plant scale under Manitoba climate and farming conditions. This treatment technology consists of solid-liquid separation, anaerobic digestion and aerobic treatment.

The funding was planned and disbursed through Manitoba Livestock Manure Management Initiative. DGH Engineering expresses its sincere thanks and appreciation to Manitoba Livestock Manure Management Initiative for their help, cooperation, and advice during the course of this study. DGH gratefully acknowledges the contributions received from Triple S Community Futures Development Corporation (Triple S), Manitoba Rural Adaptation Council Inc. (MRAC) and Sustainable Development Innovations Fund (SDIF).

DGH Engineering further extends its thanks and appreciation to Mr. and Mrs. J. Cook for providing the site for the demonstration and for their co-operation and assistance throughout the project.

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LIST of NOMENCLATURES

DO	Dissolved Oxygen
COD	Chemical Oxygen Demand
COD-Sol.	Soluble COD
COD-Tot.	Total COD
BOD	Biochemical Oxygen Demand
TKN	Total Kjeldahl Nitrogen
TKN-Sol.	Soluble TKN
TKN-Tot.	Total TKN
PO_4-P-Sol.	Soluble PO_4-P
PO_4-P-Tot.	Total PO_4-P
MC	Moisture Content
TS	Total Solids
TVS	Total Volatile Solids
SS	Suspended Solids
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
VS	Volatile Solids
F/M	Food to Microorganism Ratio
HRT	Hydraulic Retention Time
SRT	Solids Retention Time
M-R	Raw Manure
M-S	Screened Manure
An-1	1^{st} Anaerobic Basin
An-2	2^{nd} Anaerobic Basin
An-3	3^{rd} Anaerobic Basin
An-4	4^{th} Anaerobic Basin
An-5	5^{th} Anaerobic Basin
An-6	6^{th} Anaerobic Basin
A-1	1^{st} Anaerobic Basin
A-2	2^{nd} Anaerobic Basin
A-3	3^{rd} Anaerobic Basin
S-1	1^{st} Settling Basin
S-2	2^{nd} Settling Basin

EXECUTIVE SUMMARY

This report discusses the results of a project to demonstrate and evaluate a three-stage treatment system for hog manure that was transferred to Manitoba from Taiwan by a local businessman, Mr. Carlos Hon. The system, designed by experts in Taiwan, was constructed with local engineering support by DGH Engineering Ltd.

The process involves passing the manure through a solid-liquid separator to remove the larger solids; anaerobic digestion of the liquid fraction; followed by aerobic treatment. Some of the treated effluent was recycled through the barn to enhance manure removal. The balance of the treated effluent was transferred to a conventional manure storage.

The project comprised four stages. The first two consisted of commissioning, acclimatization of the microorganisms, and trouble-shooting to resolve several operational problems that included the solid-liquid separator. The third stage involved loading the plant with one-half the manure produced from the 300 head feeder barn that supplied the manure. This stage was divided into two phases; Stage III-A utilized three aerobic basins, while Stage B only used two basins with a higher aeration rate per basin. The final stage received the full manure load from the barn. The aeration strategy was the same as Stage III-B.

The plant did not achieve treatment levels that would permit discharge to surface waters, as is the case in Taiwan. Reasons for this are likely due to the differences in operational temperature between Taiwan (greater than 25°C) and the pilot plant (15 to 21°C).

Overall system efficiency averaged 98 percent removal of total COD at the low organic load rate (approximately one half of manure from the 300 head feeder barn). At the high organic load rate, overall efficiency averaged 84 percent removal of total COD. Total Kjedhal nitrogen was reduced 77 percent at the low loading rate and 46 percent at the high loading rate.

These treatment efficiencies produced an effluent that could not be discharged into surface watercourses. The effluent, however, was very effective for flushing the barn and produced a noticeable improvement in the barn air quality. The level of treatment achieved should result in dramatic reductions in odour during storage and land application as compared to untreated manure. In addition, the reduction in nitrogen and phosphorous will result in a significant reduction in the land base required for disposal.

The treatment system did not achieve the levels of efficiency reported in Taiwan. Reasons for this are likely due to the differences in temperature (greater than 25°C in Taiwan versus 15 to 21°C in the pilot plant). In addition, considerably more water is used in Taiwan (20-30L/pig-day) than in Canada (7 L/pig-day) and this could impact performance.

The greatest amount of treatment occurred in the anaerobic section of the system (approximately 50 to 75 percent reduction in total COD). The solid-liquid separator reduced total COD by 10 to 30 percent and the aerobic section reduced total COD by up to approximately 10 percent. Of the three components, the anaerobic process is considerable simpler, less costly and easier to operate. The mechanical components are much reduced in the anaerobic section.

The anaerobic basins were very stable and changes in operational conditions did not upset their performance. Particularly during the start-up and trouble-shooting stages, the loading rate was very non-uniform, however this appeared to have relatively little impact on the anaerobic basins.

In comparison, the aerobic basins were much more sensitive to changes in operational conditions.

The solid-liquid separator worked well after the manure was diluted to approximately six percent solids. The separator provided solid manure with an average moisture content of 78 percent. For optimum composting, some mixing with drier organic matter would be required.

The treatment efficiency in the aerobic section was low. This may have been due to low dissolved oxygen levels or the biomass activity was lower than expected. The recycled sludge to the aerobic basins may have been composed of an aged microbial population due to insufficient sludge removal from the settling tanks. The reduction in total COD was greatest during Stage III-B (low loading rate, two aeration basins). Dissolved oxygen levels were highest during this phase.

Both the anaerobic and aerobic sections appeared to be overdesigned in terms of volume and hydraulic retention time. At the low loading rate, most of the reduction in COD in the anaerobic basins took place in the first two of six basins. The hydraulic retention time in these first two basins was 14 days. Similarly, at the high loading rate, four anaerobic basins, representing a hydraulic retention time of 13 days, were sufficient to achieve most of the COD reduction that occurred in the anaerobic section.

The aerobic section was most efficient during Stage III-B. During this phase the majority of COD reduction occurred in the first of the two aerobic basins. The hydraulic retention time on each of these aerobic basins was eight days.

Very little biogas production was observed under the covers of the anaerobic basins, therefore gas production was not measured. The presence of methane formers was confirmed, however, the reason for the low gas production has not been determined.

Chapter 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

The management of animal manure continues to raise concerns from the general public because of its potential to create nuisance odours. When mismanaged, manure also has the potential to cause water pollution. Other environmental issues, such as greenhouse gas emissions, although not a great concern at the present time, may become an important issue in the future. In certain communities, livestock developments will only be approved if exceptional steps are taken to reduce odours and/or other nuisances. In those situations cost-effective treatment of manure could be a viable option.

1.2 Project Background

There are many environmental technologies available that can be integrated into manure management practices to treat livestock waste and provide some or all of the following objectives:

- stabilization of organic compounds;
- control of odour;
- protection of all phases of the environment (air, water and soil);
- conservation of manure nutrients;
- production of value-added products such as bio-gas;
- reduction of greenhouse gas emissions; and
- production of high quality effluent.

One strategy to develop new manure management technologies is to transfer proven technologies from other countries. To do this, it is necessary to: 1) identify appropriate waste management technologies in other swine producing countries and 2) investigate the adaptability and cost-effectiveness of these technologies under Canadian climatic conditions and hog management practices.

To initiate such a program, Mr. Dennis Hodgkinson of DGH Engineering Ltd. and Mr. Carlos Hon of Hon International Inc. visited Taiwan, a country with a sizable pork industry on a small land base. This country has taken some unique steps to apply environmentally sound technologies in swine waste management.

The results of their site visits and investigation showed that one of treatment technologies most commonly practiced in Taiwan performed reliably and appeared to have potential for use in Western Canada. This treatment technology consisted of a three-stage process that included solid/liquid separation, anaerobic digestion and aerobic treatment. The treated effluent was used as flush water in animal houses, for irrigation or for discharge to watercourses.

The goal of Hon International Inc. was to introduce and demonstrate the technology and to evaluate the applicability of the Taiwanese three-stage technology under Canadian climatic conditions. To do so, a pilot plant treatment system was designed by Taiwanese expertise, and constructed in conjunction with an existing feeder barn at the farm of Mr. and Mrs. J. Cook of Teulon, in Manitoba. Local engineering support was provided by DGH Engineering Ltd. The construction work was finished in the spring of 1998. During the course of this development, Mr. Hon encountered significant financial difficulties and also became physically disabled. The project had been supported by economic development funding from the Province of Manitoba. Representatives of the funding agency requested that DGH develop a strategy to commission and operate the plant to complete the evaluation and demonstration of the technology. To this end, a proposal was prepared by DGH and submitted to the Manitoba Livestock Waste Management Initiative.

On December 1998, DGH Engineering Ltd. received a total funding of $99,300 to operate the pilot plant and do a performance evaluation of the system. The project started on January 1999 and continued to April 10, 2000. This report presents the results of this evaluation.

Chapter 2

LITERATURE REVIEW

2.1 Manure Treatment

There is a wide range of treatment methods available for livestock waste management. However, only some will be realistic options for meeting the specific manure problems encountered by individual producers. Evaluation and selection of treatment options are based on many parameters including the main purpose of the treatment, cost, adaptability, reliability, safety, and their practicality in the farming environment.

On the basis of the process principals, treatment processes are usually classified as physical, thermal, chemical and biological.

2.2 Physical Treatment

In general, physical treatment refers to the solid-liquid separation of the liquid or slurry manure. Solid-liquid separation is often accompanied by further processing of the solid and liquid fractions.

2.2.1 Solid-Liquid Separation

Solid-liquid separation has been widely used for treating industrial and municipal wastewaters. Because of the associated costs, which include capital facilities and ongoing labour and operational costs, it has not been widely accepted by farmers for animal manure management (Zhu, J. 1999).

Solid-liquid separation can be beneficial to farmers in terms of producing nutrient rich organic solids, facilitating the transportation and storage of the liquid fraction, and reducing the treatment load for subsequent treatment units. Solid-liquid separation concentrates organic solids and nutrients into a small fraction for utilization. The separated solids, typically 10-20% of the original volume, represent a reduced environmental risk as the nutrients contained are less mobile. This material can be spread locally or, if necessary, composted to produce value-added organic material suitable for soil conditioning.

2.2.2 Impact on Odour Reduction

Solid-liquid separation divides raw manure into two fractions: solids and liquid. Separation by itself does not reduce odour generation. Special care should be provided for the separated solid and liquid fraction. The separated solids are still quite wet, with a moisture content of above 70% (Zhu, J. 1999). If left alone in the field, the solids will naturally undergo anaerobic decomposition and generation of odour. Composting or drying immediately after separation is required to keep odours from manure solids at a minimum level. As far as the liquid portion of manure is concerned, odour generation potential depends largely on the amount of organic matter remaining in the liquid and the management of the liquid in the subsequent storage and/or treatment units. Theoretically, it is expected that odour generation rate will be reduced in liquid fraction because of the reduction in biodegradable organic matter as compared with the raw manure. The separated liquid is free-flowing with a dry matter content reduction of approximately 25% (Burton C.H., 1997).

2.2.3 Separator Types

Solid/liquid separation processes include sedimentation, screening, centrifugation, and filtration (Zhang and Westerman, 1997). Sedimentation is most effective for treating dilute wastewaters such as feedlot runoff. The solid-liquid separation occurs as a result of settling by particles of a specific gravity greater than one. It is reported that the settling of the solids is usually hindered when the suspended solids in the wastewater exceeds 1% [Sobel A.T., 1966). Manure flow rate, solids settling rate and detention time are the primary design parameters for sedimentation basins

A quicker separation can be obtained by a wide ranges of mechanical separators with different operating principles. These range from the cheapest static run-down screens, through medium cost units such as rotating screens to the most elaborate screw presses and centrifuges.

Screens are the most extensively tested separators thus so far. The screen separators that have been used with animal manure include stationary, vibrating, and rotating screens. The performance of screen separators is mainly determined by screen opening size, flow rate and the characteristics of manure to be separated (initial solids content and particle size distribution). Screens with openings of 1-3 mm are mostly used for the removal of large particles. Screens with smaller openings tend to experience clogging problems.

Centrifuges and hydrocyclones have also been tested with different types of animal manure, but their relatively high costs and complex structures have not made them a popular choice for animal producers. Because of the way centrifuges have been built in the past, they typically have a greater capacity than would be needed by most individual swine producers. The solid fraction from a centrifuge may be as dry as 20 to 25 percent solids depending on the centrifuge and the use of filtering aids.

Presses are designed for solids dewatering. The presses use the principle of pressurizing solids with rollers or screws against an opposing screen or a perforated belt, through which the liquid is removed. Typical types of presses mainly include roller, belt, and screw presses. Belt presses are found to have higher separation efficiencies and produce drier solids than the screen separators, but their structures and operation are more complicated and costs are higher. It has been reported that swine manure handling systems that maintain a total solids of 50 g/L or more can gain the most benefit from using a screw press. In general, the performance data for the use of screw presses and roller presses in animal manure handling are lacking in the literature (Zhang and Westerman, 1997).

2.2.4 Performance Evaluation

The performance of sedimentation basins and mechanical separators is evaluated by the amount of total solids removed from the influent manure and moisture content of solids separated (Zhu J., 1999). The data on performance efficiencies of some of these separators used for hog manure (Zhang and Westerman, 1997) is summarized in Table 1. For swine manure, the efficiency of the screens with 0.86 – 1 mm openings is less than 52%, the efficiency of a belt press with a fine pore size (0.1 mm) is 47 – 59%, and the efficiency of a centrifuge is 45%.

2.2.5 Economics of Mechanical Separators

Solids-liquid separation, like other operations on animal farms, requires initial capital investment for the separator system and installation and labour and other costs for the system's operation, maintenance and repair (Zhang and Westerman, 1997). The retail price of a mechanical separator varies from US $10,000 to more than 50,000, depending on the type of the separator and its throughput capacity (amount of wastewater processed per unit time). The throughput capacity of a typical separator varies from 6 to 38 L/s (Zhu J., 1999). With the same capacity, screens are usually less expensive than presses and centrifuges. Screens, especially stationary and rotating screens generally perform better with manure containing low total solids (less than 5%) while presses and centrifuges are more efficient with manure of higher total solids level. In general, the economics of using solids-liquid separation on animal farms is determined by the amount of manure to be processed, the extent of solids removal from the manure, and the potential for solids reuse and value recovery.

Table 1: Performance of Mechanical Separators Used for Swine Manure.
(Adapted from Zhang and Westerman, 1997)

Separator Type	Screen Opening (mm)	TS in Manure (%)	Separation Efficiency (%)					TS in Solids (%)	Flow Rate (l/min)
			TS*	VS	COD	TKN	TP		
Stationary Screen	1.5	0.2-0.7	9	-	24	-	-	6	235
	1.0	0.2-0.7	35	-	69	-	-	9	123
	1.0	1.0-4.5	6-31	5-38	0-32	3-6	2-12	5	-
Vibrating Screen	1.7	1.5	3	-	6	-	-	17	37-103
	0.841	1.5-2.9	10	-	1-14	-	-	18-19	15-103
	0.516	1.8	27	-	24	-	-	20	37-57
	0.516	3.6	21-52	25-55	17-49	5-32	17-34	9-17	38-150
	0.39	0.2-0.7	22	28	16	-	-	16	67
	0.44	1-4.5	15-25	18-38	13-26	2-5	1-15	13	-
	0.104	3.6	50-67	54-70	48-59	33-51	34-59	2-8	38-150
Rotating Screen	0.75	2.5-4.12	4-8	-	4	-	-	16-17	80-307
	0.8	1-4.5	5-24	9-31	2-19	5-11	3-9	12	-
Belt Press	0.1	3-8	47-59	-	39-40	32-35	18-21	14-18	-
Centrifuge	-	1-7.5	15-61	18-65	7.8-44	3.4-32	58-68	16-27	-

* TS – Total Solids
COD – Chemical Oxygen Demand
TP – Total Phosphorous
VS – Volatile Solids
TKN – Total Kjeldahl Nitrogen

2.3 Biological Treatment

Animal manure contains organic compounds that are highly biodegradable. Manure naturally undergoes anaerobic decomposition, resulting in the release of obnoxious odours. The use of biological treatment processes in animal manure management is mainly intended to: a) achieve stabilization of the organic content of the manure, b) avoid odour generation, and c) produce value-added products whenever possible. Biological treatments may also yield useful by-products such as biogas or saleable compost.

Biological treatment processes can be classified into two major groups; anaerobic (without oxygen) and aerobic (with oxygen), depending on the presence of oxygen in the treatment environment.

2.3.1 Anaerobic Treatment

Anaerobic treatment is a biological process that takes place in the absence of free oxygen in the environment. During this process, the organic material is converted to a variety of intermediate and end products including methane (CH_4) and carbon dioxide (CO_2). A complete anaerobic digestion of organic substances can be shown as:

$$\text{Organics (C, H, O, N, S)} \longrightarrow CH_4 + CO_2 + NH_4^+ + H_2S$$

Methane (CH_4) and carbon dioxide (CO_2), collectively called biogas, are the principal end products of controlled anaerobic digestion. Biogas contains 60-70% methane and can be used as a fuel for heating or electrical power generation.

During anaerobic digestion, a consortium of anaerobic organisms work together to convert and stabilize organic wastes. One group of organisms is responsible for hydrolyzing high molecular weight compounds into soluble compounds that are suitable as a source of energy and cell carbon. A second group of anaerobic bacteria ferments the breakdown products to simple organic acids (e.g. acetic acid). This group of microorganisms is often identified in the literature as “acidogens” or “acid formers”. A third group of microorganisms converts the intermediate compounds into simpler end products, mainly methane and carbon dioxide. The bacteria responsible for this conversion are collectively called “methanogens” or “methane formers”.

2.3.1.a Factors Affecting Anaerobic Digestion

To maintain an anaerobic treatment system that will stabilize organic waste efficiently, the nonmethanogenic and methanogenic bacteria must be in a state of dynamic equilibrium. To establish and maintain such a state, all the parameters affecting the process performance should be monitored and kept within the acceptable range. The most important of these parameters are pH, alkalinity, temperature, nutrients, retention time, toxic material, and organic loading.

pH and Alkalinity - Methanogenic bacteria are very sensitive to pH. The pH in a digester is a function of bicarbonate alkalinity, CO_2 partial pressure, ammonia, and concentration of volatile fatty acids. The pH of the aqueous environment should range from 6.6 to 7.6 (Tchobanoglous and Burton, 1991). The optimum range is reported between 7.0 and 7.2 (McCarty P.L. 1964).

Sufficient alkalinity should be present to ensure that the pH will not drop below 6.2 because the methane bacteria cannot function below this point (Tchobanoglous and Burton, 1991). Bicarbonate alkalinity in the range of 2500 to 5000 mg/L provides a safe buffering capacity. Ammonia in the animal manure helps maintain the process stability by increasing the bicarbonate buffering capacity as well as the pH. However, high pH can become a problem if high levels of ammonia are generated at high organic loading rates.

Excess volatile fatty acids in the digesters can be toxic to the methane bacteria. The concentration of these compounds should be kept below 2000 mg/L for a stable digestion process (McCarty and McKinney, 1961).

Temperature - Anaerobic digestion of organic wastes can occur under a wide range of temperature. Three temperature ranges have been reported for anaerobic digestion; the psychrophilic range (10-20ºC), the mesophilic range (20-45 ºC, typically 35ºC), and the thermophilic range (45-60ºC, typically 55ºC). Conventional anaerobic digesters are commonly designed to operate in either the mesophilic or thermophilic range. The rate of digestion increases with increasing temperature. As a result, digestion at higher temperature ranges than psychrophilic, handles higher organic loading rates and requires shorter retention time and is therefore more space efficient. The conventional anaerobic digestion of animal manure has been tried in farm-scale digesters at several locations across Canada during 1975-1985 and found to be unsuccessful because of high heating costs, the need for skilled operators and operational instability.

Psychrophilic digestion of animal manure has been primarily associated with covered lagoons operating at ambient temperatures. Past studies have shown that psychrophilic anaerobic digestion is a biotechnology suitable for the treatment of animal manure (O'Rourke, 1968; Stevens and Schulte, 1977; Ke-Xin and Nian-Gua, 1980; Wellinger and Kaufmann, 1982; Chandler et al., 1983; Cullimore et al., 1985; Lo and Liao, 1986; Sutter and Wellinger, 1987; Balsari and Bozza, 1988; and Safley and Westerman, 1992, 1994). In 1992, Dr. Daniel Masse (Agriculture and Agri-Food Canada, Quebec) developed a new low temperature anaerobic digestion system for the treatment of swine manure and other organic waste. The system consisting of a set of sequencing batch reactors has been tested and optimized at the lab-scale and pilot-plant scale. The results have indicated excellent performance with respect to the reduction of odour, recovery of energy and operational stability (Massé et.al., 1996 & Massé et al., 1997). The pilot plant studies have indicated that this technology is very promising for animal waste management. A full-scale prototype of this system (for a 1000 head feeder barn) was built in Quebec in 1999 and at present is under performance evaluation.

Nutrients - Nutrients such as nitrogen, phosphorus, sulfur, and trace elements such as sodium, potassium, iron, calcium, etc. are required for bacterial growth. Animal manure usually contains all the required macro and micro-nutrients in adequate quantities. The relative proportion of nutrients is an important factor for methane production. It is reported (Hills D.J., 1979) that the optimum level of carbon to nitrogen (C:N) ratio for anaerobic digestion of agricultural wastes is around 25. Animal manure generally has a C:N ratio between six and ten, therefore an increase in methane yields can be achieved by adding carbonaceous material (e.g. crop residues), to animal manure.

Solids retention time (SRT) - The SRT must be long enough to ensure a sufficient population of anaerobic bacteria. The minimum SRT varies with the digester temperature and usually increases with a decrease in temperature. For mesophilic (35 ºC) digesters, the SRT is higher than 10 days.

Toxic materials - Excess quantities of organic and inorganic substances, including volatile fatty acids, ammonia, metal ions and antibiotics can create toxicity for the anaerobic bacteria. It is reported [3] that at concentrations between 1500 and 3000 mg/L of total ammonia nitrogen, and a pH greater than 7.4, the ammonia concentration may inhibit methane production. At concentrations above 3000 mg/L, ammonia becomes toxic regardless of pH. It is generally recommended that the concentration of total ammonia nitrogen be maintained below 2000 mg/L. Antibiotics used in livestock rations can also inhibit or completely stop methane production [EPRI Report, 1997].

2.3.1.b Anaerobic Treatment Systems

The most common anaerobic treatment systems in use for animal manure are anaerobic lagoons.

Anaerobic lagoons have found widespread application in the treatment of animal waste in warmer climates. Low initial cost, ease of operation and the convenience of loading manure by gravity flow are the major advantages of anaerobic lagoons. The main drawback is the release of odours from the open lagoon surface, which intensify during spring warm-up or when they are overloaded. However, the odour problems can be solved if the lagoons are covered.

Earthen manure storages in Western Canada are not considered anaerobic lagoons. Although there is anaerobic activity during summer months, during winter anaerobic activity is nonexistent. The level of treatment is therefore very limited.

Anaerobic digesters are air-tight, enclosed vessels. Manure, introduced continuously or intermittently, is retained in the reactor for varying periods of time in a controlled environment, thus resulting in higher digestion rates and smaller volume requirements than anaerobic lagoons. Heating and mixing of the digester's content is usually provided to maximize treatment efficiency and biogas production. Anaerobic digesters of these types are suitable for treating solid or slurry manure from feedlots or confined buildings. When dealing with dilute manure such as flushed manure, new biomass-retaining (high-rate) digesters are being developed and adapted to improve the economics of treating liquid manure. Biomass-retaining digesters are designed and developed to ensure the bacterial cells and solids are retained longer than the treated liquid fraction. Major types of biomass-retaining digesters include anaerobic sequencing batch reactor (ASBR), anaerobic contact reactor, upflow sludge blanket reactor (UASB), anaerobic filter, and fluidized bed reactor (EPRI Report, 1997).

2.3.1.c Major Advantages of Anaerobic Digesters

The advantages of anaerobic digestors are:

- reduction of offensive odours;
- energy recovery (biogas);
- stabilization of organic substances (both soluble and solid fractions);
- conservation of the fertilizer value of manure;
- destruction of pathogens if high temperature and adequate retention time are provided; and
- co-fermentation by taking up other organic wastes.

2.3.1.d Major Disadvantages of the Conventional Anaerobic Digesters

- high capital cost - cost (a function of economy of scale);
- highly technical process requires skilled operators; and
- highly sensitive to operational and environmental parameters.

2.3.2 Aerobic Treatment

Aerobic treatment is a biological process that requires oxygen. During this process, biodegradable dissolved organic material present in manure will be degraded by aerobic bacteria that use oxygen as an electron acceptor in their metabolic reactions. The degree of oxidation depends on the amount of oxygen provided, the temperature and the retention time. In general, the conversion of organic matter occurs according to the following stoichiometry:

$$\text{Organics (C, H, O, N, S)} + O_2 \longrightarrow CO_2 + H_2O + NH_3 + \underbrace{C_5H_7NO_2}_{\text{New bacterial cells}} + \text{other end products}$$

Nitrogen in livestock slurries is present in both the inorganic (ammonia) and organic forms. Nitrogen composition, however, can undergo changes during aerobic treatment. These changes are dependent on the treatment time, temperature and concentration of dissolved oxygen (Svoboda, 1995). Between five and 35 percent of slurry organic nitrogen can be converted to ammonia nitrogen by aeration (Bicudo J., 1999). Under proper operational conditions, ammonia nitrogen can be oxidized and converted to nitrate through the nitrification process. Nitrification is a biological two step process. In the first step, ammonia is oxidized to nitrite-nitrogen. The bacteria responsible for this conversion are known as *Nitrosomonas*. Nitrite-nitrogen is then oxidized to nitrate-nitrogen by another group of bacteria called *Nitrobacter*. In the absence of nitrification, large ammonia losses are likely, particularly if air flow rates are excessive (Bicudo J., 1999). Nitrogen transformations during aerobic treatment can be summarized as:

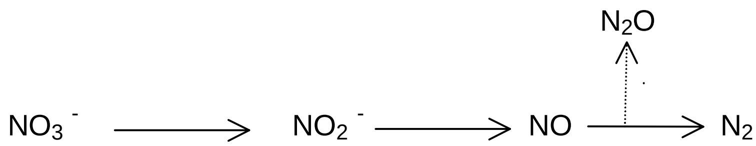
$$\text{Organic-N} \xrightarrow{\text{Mineralization Bacteria}} NH_4^+$$

$$NH_4^+ \xrightarrow{\text{Nirrosomonas}} NO_2^- + 2H^+ + H_2O$$

$$NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} NO_3^-$$

Nitrifying bacteria are sensitive organisms and extremely susceptible to a wide variety of inhibitors. Dissolved oxygen (DO) concentrations above 1 mg/L are essential for nitrification to occur. If DO levels drop below this value, oxygen becomes the limiting nutrient and nitrification slows or ceases (Mecalf & Eddy, 1991). During storage of the treated slurry or during treatment, if the aeration level is kept close to the minimum requirement of nitrifying bacteria

(Smith and Evans, 1982), nitrate is converted to nitrogen (N_2) and/or nitrous oxide (N_2O) gases through the biological process of denitrification, as summarized below. Nitrification and denitrification can occur simultaneously in the same tank. Denitrification is a source of nitrogen loss and reduces the fertilizer value of manure.



Sulfur compounds in the manure are converted to sulfate (SO_4^{2-}) under aerobic conditions. This prevents the emission of odour causing compounds such as sulfide and mercaptans to the atmosphere.

Volatile fatty acids (VFA) are easily degraded under aerobic conditions and their destruction is independent of treatment time in the range of one to 4.5 days (Bicudo J., 1999). As described by Williams et al. (1989), volatile fatty acids are the main soluble biodegradable components of slurry and are probably the most readily biodegradable substrate, because simple sugars are unlikely to be found in significant quantities. As a result, as treatment time decreases, VFA becomes the largest fraction of substrate degraded.

2.3.2.a Oxygen Requirement and Aeration

An adequate supply of oxygen will enhance aerobic treatment efficiency. Adequate aeration involves dissolving enough oxygen into liquid manure to replace an anaerobic system with an aerobic environment for microbial activity. Under such conditions, organic matter is rapidly oxidized to relatively harmless products such as carbon dioxide and water. The removal of the organic material eliminates the main cause of offensive odours associated with animal manures such as organic acids, indoles, nitrogen and sulfur compounds, etc. In activated sludge sewage treatment plants, the dissolved oxygen (DO) concentration is usually kept around 2 mg/L in the aeration tanks to ensure sufficient supply of DO for microbial activity. Adequate air supply is also necessary to provide a thorough mixing within the tanks.

The theoretical oxygen requirements can be determined from the biochemical oxygen demand (BOD) or chemical oxygen demand (COD) of the waste. The minimum oxygen capacity should be twice the total daily BOD loading for complete oxidation of organic matter and also for converting ammonia (NH_3) to nitrate (NO_3) through nitrification processes, with a hydraulic retention time (HRT) of 10 days or more (NZAEI, 1984).

Burton et al. (1998) have recently reported that a farm scale continuous aerobic treatment was able to reduce odour concentrations by 50 to 75% with treatment times between 1.7 and 6.3 days.

Since complete stabilization of livestock manure by aerobic treatment is not normally economically justifiable (Westerman and Zhang, 1997), lower levels of aeration have been recommended for partial odour control. An oxygenation capacity to supply 1/3 to 1/2 the BOD load was recommended for partial odour treatment (NZAEI, 1984). Using a lower rate of aeration (compared to that needed for complete stabilization) reduces the release of volatile acids and other odourous gases and compounds as well as allowing some oxidation to less odourous compounds (Westerman and Zhang, 1997).

The aerator can be of a number of types (pressure aeration, suction aeration, and surface aeration systems), but bubbler systems are the most common due to their low cost and flexibility. The aeration basin can be of any design but efficiency is generally improved with the depth of liquid. Suction and surface aerators are better for more concentrated manure. Diffuser aerators offer the highest efficiencies but only work effectively in dilute waste due to their capacities for oxygen transfer. Systems requiring a large supply of oxygen per unit volume require a more intensive aeration implying a high degree of mixing as well. With high airflow rates, foam control becomes more important. Foam is usually controlled by intermittent aeration cycles or by mechanical foam breakers.

Aerobic treatment is not widely accepted by livestock producers because of the high operational cost associated with the aeration. Nevertheless, some form of aerobic treatment could be considered a desirable alternative in odour control management especially for producers with a high risk of odour nuisance liability.

2.3.2.b Advantages of Aerobic Slurry Treatment

The advantages of aerobic treatment include:

- reduction of offensive odour and methane emission during storage and land application of manure;
- stabilization of nitrogen through the conversion of ammonia nitrogen to nitrates;
- stabilization of manure organic content;
- some improvement of the homogeneity of the manure; and
- pathogen reduction (with temperatures between 50°C-60°C.

2.3.2.c Disadvantage of Aerobic Slurry Treatment

- High costs, especially operating costs. The aeration of animal manure for complete oxidation of organic matter can be very costly. The total power cost for running the aeration system of a completely aerated lagoon (DO level of 1 to 2 mg/L) for a finishing pig operation was estimated to be $US 0.03/day per finishing pig space. If 2.5 pigs are turned over per year per pig space, the cost of electricity for aeration is US $4.40 per pig produced (EPRI Report, 1997). Therefore aeration of animal manure for complete removal of biodegradable dissolved organic compounds is technically feasible but not economically viable for animal operations. Lower levels of aeration to control odour to certain extent reduces the cost. If one third of the biochemical oxygen demand (BOD) load is used for odor control, the electricity cost for running the aeration system will be $US 0.01/day per finishing pig space, or US $1.90 per pig produced (EPRI Report, 1997).

- Emissions of odour, ammonia and other gases when adequate aeration is not provided or is insufficient;
- Loss of nitrogen (fertilizing-value of manure) through ammonia volatilization, and/or through nitrifying/denitrifying reactions;
- Foaming;

- Aeration, on its own, is limited to the more reactive organic components of the slurry. There remains a relatively inert fraction mainly composed of insoluble material. This can account for up to 70% of the total organic load as indicated by chemical oxygen demand (COD) and is largely unaffected over the short treatment period of less than five days (Burton, 1997); and
- Some type of pretreatment (e.g. solid/liquid separation process) is essential in order to achieve an efficient treatment process.

Chapter 3

PILOT PLANT

3.1 Location of Pilot Plant

The pilot plant has been constructed in conjunction with an existing 300 head feeder barn at the farm of Mr. and Mrs. J. Cook of Teulon. The barn is a conventional feeder barn with slatted floors and an under floor pit with an average depth of 600 mm. Prior to commencement of the pilot plant, manure handling included accumulation of manure in the pit, regular discharge of manure from the pit to an existing below-grade concrete storage tank and land application of the stored manure. Manure would accumulate in the pit to a depth of approximately 450 mm, at which time the pit plug would be removed to allow a gravity drainage of the manure to the storage. Average manure production was estimated to be 6.2 L/pig-day or a total of 1.86 m^3/d.

The average weight of the pigs is about 23 kg upon arrival and 110 kg at market. The growing period is 90-100 days. The barn is empty for a period of two to three weeks between two consecutive batches for cleaning and disinfection.

3.2 Pilot Plant: Treatment Process Components

The treatment system included the following sequential processes:

Solid-liquid separation: During this process, manure would pass through a mechanical separator in order to separate solids from the liquid fraction of manure. The separated solids accumulated under the separator and were periodically removed by a front-end loader and spread on farm land. In a Taiwanese report it is indicated that solid-liquid separation of the type used in this study can remove 50-60% of the total organic matter and 50-70% of the suspended solids in pig waste slurries. The solid liquid separation also reduces the organic loads to the following units and enhances pumping and land application of the waste.

Anaerobic digestion: The screened manure passed through a series of six anaerobic basins where digestion of manure occurred. Although the basins represented plug-flow type reactors, the up-flow and down-flow passage of manure through these basins likely provides some degree of mixing. The main purpose of anaerobic digestion is to stabilized and reduce the amount of organic matter contained in manure. Any reduction in the amount of organic compounds will decrease the potential for odour generation during storage and land application. Furthermore, anaerobic pretreatment of manure reduces the organic loads to the following treatment units, in this case aerobic basins. This will enhance aeration performance and treatment efficiency. The first anaerobic basin was heated by hot water coils to keep the temperature around 20 ºC. The settled solids in anaerobic basins could be discharged to the existing manure storage in the farm. An 80% removal of BOD and 80-87% removal of solids were reported for the anaerobic treatment of this type for hog manure in Taiwan.

Aerobic treatment: Following the anaerobic units was a series of 3 aerobic basins. The aeration was supplied by two compressors and a grid of diffusers located in each basin. The objective of this post aerobic treatment is to oxidize and reduce the remaining organic matter left from anaerobic process. The aerobic process significantly reduces odour-producing compounds.

Settling basins: The effluent from aerobic process passes through two settling basins in series. The effluent from the aeration basins where agitation and mixing is involved, contains suspended solids composed of microbial biomass (activated sludge) and other particulate matter. Quiescent conditions in settling basins allows for removal of some of the suspended solids. The settled solids (activated sludge) could be returned to the aeration chambers to enhance treatment process or discharged to the existing manure storage in the farm. The effluent from the settling units (final effluent) was recycled to the barn to hydraulically remove manure and the excess discharged to the manure storage.

3.3 Pilot Plant: Structural and Mechanical Components

3.3.1 Structural Building

The major components of the pilot plant are contained in a post frame building that measures 11 by 14.6 metres. The structure is 3.6 metres in height and contained a concrete floor. As well, a 3.36 metre sliding door was installed to facilitate the removal of accumulated separated solids by front end loader throughout the duration of the project. Drawings for the pilot plant construction are enclosed in Appendix B.

3.3.2 Treatment System

The treatment system consists of a mechanical screen separator, six anaerobic basins, three aerobic basins, and two settling basins. All treatment basins were constructed with 200 mm thick reinforced concrete walls. The basins are 3.6 m in depth, with 1.2 m above the floor slab and 2.4 m below grade.

3.3.3 Mechanical Screen and Auger

The mechanical screening unit is located placed at the northeast corner of the treatment system. The unit consists of a screen, approximately 600 mm wide X 900 mm long at an angle of 60° from horizontal. A 75 mm diameter line from a pump located in a wet well fills a reservoir and manure overflows onto the screen. The solids are retained on the screen and collect in a auger section at the end of the screen. The auger further removes liquid using a screened section in the auger housing. The liquid enters the anaerobic basins, and the solids are deposited onto the floor where they are collected and removed by a front end loader. A washing system located behind the screen is controlled by a timer that cleans the screen at prescribed time intervals to prevent clogging.

3.3.4 Anaerobic Basins

As seen in Appendix B, anaerobic basins 1 to 3 are sloped 30° towards a 1000 X 1525 mm sludge collection basin that varies in depth from 2590 to 3660 mm. These sludge collection basins contain PVC piping that removes the sludge at prescribed times to an existing concrete storage.

The dimensions of the anaerobic basins vary somewhat depending on their location. A summary of their dimensions and volumes are as follows:

Table 3.1: Anaerobic Basin Dimensions

Basin #	Length (mm)	Width (mm)	Depth	Effective Depth* (mm)	Volume (m^3)
An-1	2135	1525	3660	-	6.7
An-2	3355	1525	3660	-	10.5
An-3	3355	1625	3660	-	11.2
An-4	2135	1625	3660	2970	15.6
An-5	3355	1625	3660	2970	16.6
An-6	3355	1625	3660	2970	16.6

* Effective depth = Depth – 686 mm (not used for sloped basins).

Connecting anaerobic basins An-1 to An-2, An-3 to An-4, and An-5 to An-6 are three 300 x 300 mm transfer ports 1000 mm above the bottom of the basins. To provide manure flow through the rest of the anaerobic section of the treatment system, 150 x 150 mm transfer channels located 530 mm below the top of the basins were created (connecting An-2 to An-3 and An-4 to An-5)

The six anaerobic basins were covered and sealed with PVC material with gas emission ports exiting at the top of each basin. The emission ports were attached to 50 mm diameter PVC piping and vented out to the atmosphere through a gas trap to prevent oxygen re-entering the cells from the atmosphere.

3.3.5 Aerobic Basins

The third stage of the treatment system consists of three aerobic basins. These aerobic basins are constructed using 200 mm reinforced concrete walls as well. The volumes of the aerobic basins are shown in Table 3.2.

The three aerobic basins have 12 mm PVC piping extending to the bottom of each basin. There the pipes direct compressed air into one of five diffusers (one in each corner and one in the centre of the basin). These basins are also connected with 150 x 150 mm transfer openings through connecting walls of the basins.

Table 3.2: Aerobic Basin Dimensions

Basin #	Length (mm)	Width (mm)	Depth (mm)	Effective Depth (mm)	Volume (m^3)
A-1	3355	1625	3660	2790	16.6
A-2	3355	1625	3660	2790	16.6
A-3	3355	1525	3660	2790	15.2

3.3.6 Settling Basins

Two settling basins comprise the last stage of treatment for the pilot plant. These basins have the bottom 600 mm sloped to a 400 x 400 x 150 mm sump pit. Within the sump pit is the sludge removal system comprised of 12 mm PVC pipe with 12 holes at 19 mm to remove the accumulated sludge.

Table 3.3: Settling Basin Dimensions

Basin #	Length (mm)	Width (mm)	Depth (mm)	Effective Depth (mm)	Volume (m^3)
Settling 1 (S-1)	1575	1525	3660	2970	7.1
Settling 2 (S-2)	1575	1525	3660	2970	7.1

3.3.7 Mechanical Systems

To provide space heating to the pilot plant, two 4000 watt heaters were installed to ensure the room temperature within the facility remained above 20°C. An exhaust fan located on the west wall of the facility prevented any build-up of gases. To ensure anaerobic micro-organisms remained active, the first anaerobic basin was maintained at a temperature between 19°C and 22°C utilizing a 3000 watt hot water tank. Heated water ran through tubing coiled within the basin, maintaining the contents of the basin at the required temperature.

Two control panels were utilized within the pilot plant. One housed timers and relays that operated the influent pump, auger, and screen washer, and the other (main) panel housed timers that operated the sludge removal systems for anaerobic, aerobic, and settling basins, aerators, and the effluent pump.

The manure was collected in a wet well located at the north-east corner of the barn. An influent pump was capable of transferring approximately five L/s to the treatment system. The manure was transferred to the pilot plant by 75 mm diameter PVC piping extending from the wet well to the mechanical screener.

An overflow line was installed to allow excess manure pumped through the influent line to return to the wet well for future treatment. Manure flow to the mechanical screener was controlled with valves installed on the overflow line and also on the influent line just prior to the screener itself. By adjusting both of these valves a constant flow could be maintained to the screener.

To return effluent back to the barn for recycling or to the concrete storage basin, an effluent pump was located in the final settling tank. This pump utilized two probes that controlled the liquid level. Each time the effluent pump operated it removed approximately 0.9 m^3.

3.3.8 Sampling Ports

Sampling ports were located at different locations along the flow pathway to provide adequate samples for evaluation of the treatment system and its components. The locations of these ports were as follows:

- influent line to the mechanical screen (raw manure sample);
- screen discharge line (screened manure sample);
- close to the discharge port of second anaerobic basin;
- close to the discharge port of fourth anaerobic basin;
- close to the discharge port of the sixth anaerobic basin;
- first, second and third aerobic basins; and
- last effluent basin, close to the discharge line.

The samples of separated solids were taken directly from the fresh accumulated pile.

The samples were kept in a cooler and sent to the Environmental Engineering Lab., Department of Civil and Geological Engineering, University of Manitoba for analysis of the following parameters:

- chemical oxygen demand (COD);
- total solids (TS), volatile solids (VS), suspended solids (SS);
- dry matter content of separated solids;
- ammonia and organic nitrogen; and
- phosphorous.

Chapter 4

PILOT PLANT OPERATION

4.1 Operational Stages

The operation of the pilot plant could be differentiated into four general stages as follows:

4.1.1 Stage I: Preliminary Preparations and Acclimation of Anaerobic Microorganisms (December 1998 to early May 1999)

The major activities during this period were:

- preliminary preparation of the system which included check up of the influent and effluent pumps, aeration pumps, control key boards, set-up of the timers, installation of heating system in the first anaerobic basin and a heater in the wet-well, installation and improvement of sampling ports and some of the pipe lines, etc.

- Start-up of the system and acclimation of the anaerobic microorganisms to the temperature range of 18 to 22 ºC.

The actual start-up of the system began on the last week of January with filling the anaerobic basins with the seed (anaerobic sludge) shipped to the site from The North-End Water Pollution Control Centre, City of Winnipeg. About 80 m^3 of the sludge from the anaerobic digestion tanks of this treatment plant were transferred to the project site and fed to the anaerobic basins. At the North-End Water Pollution Control Centre, these microorganisms (seed) were operating at a temperature of 37ºC. Furthermore, their substrate were mainly composed of primary and activated sludge. The anaerobic microorganisms, especially methanogens, are very sensitive to changes in the operational conditions and it takes a long time for them to adjust to new conditions. As a result, an adaptation time period was required for these microorganisms to become adapted to their new operational conditions; a temperature of 20ºC or less in the anaerobic basins and the use of manure as their feed material.

A period of about 25 days (January 23 – February 22) of no feeding at an average temperature of 20 ºC was allowed for partial adaptation of the biomass to the temperature change. From February 23rd to early May, the system was fed intermittently on a batch-schedule (once every 10 days) with a quantity of raw manure equivalent to the organic load rate of 0.15-0.2 kg COD per m^3 of total anaerobic basin volume per day. This was equivalent to an organic loading rate of 0.4 to 0.6 kg COD/m^3-d for the first anaerobic basin.

Continuous feeding of the system was not possible at this stage as the screen device did not function properly. The screen would clog in the first few minutes of startup, resulting in overflowing manure. The screen was therefore disconnected and the system was fed with raw manure.

4.1.2 **Stage II:** Trouble-shooting and Fine tuning
(Early May to September, 1999)

During this period the following improvements were made:

- The screening problem was investigated and resolved. Following on-site observations and a review of the literature, it was determined that dilution of the raw manure and a reduction in flow rate were required for the screen to operate properly. In Taiwan, where this type of screen is in common use, the amount of manure produced by a feeder pig is about 20 to 30 litres per day (including wash water), while in Manitoba this value is in the range of six to eight litres per day. The pig manure in Taiwan is therefore three to four times more dilute than the manure from Canadian barns.

- Changes in the piping and valving were made to reduce the flow rate, and allow the return of the effluent to the barn for manure dilution.

  Up to June of 99, before the correction of screen separator, the system was fed intermittently with raw manure following the previous schedule. During this time, the organic loading rate to anaerobic basins increased to an average range of 0.2 to 0.25 kg COD/m^3-d in order to acclimatize the anaerobic bacteria gradually to higher loads.

- On June 4th, 1999, the other basins (aerobic and settling) were filled with water, aeration pumps were set in operation and the system was allowed to perform continuously. The effluent from the system was totally returned to the barn to provide adequate dilution. The system was operated for a period of almost two weeks. However, the operation had to be suspended as a significant leakage was observed within three basins. The leaks were located and repaired in the basins. Shortly after this work was completed, the pigs were ready to market. The barn was empty for a period about 40 days until mid August.

- During the down period, the system was intermittently fed (once every 10 days) with the stored manure from the barn pit. The intermittent feeding was continued until late September due to minor operational problems such as plugging of the barn transfer line to the wet-well and influent pump with the straw used in the barn.

  During this period of operational difficulties sampling and analysis was reduced to a minimum. Sufficient sampling, however, was undertaken to ensure that key anaerobic environmental parameters such as temperature, pH and alkalinity were within the ranges suitable for microbial activity.

4.1.3 **Stage III:** Continuous Operation, Low Organic Loading
(Late September 1999 to March 10, 2000)

During stage III of the operation, the system was continuously fed at a daily flow rate of approximately 1.85 m^3/d half of the total manure produced in the barn. The organic loading rate to the anaerobic basins ranged from 1.2 to 2.1 kg COD-Tot./m^3-d. The excess manure was discharged to the existing manure storage tank in the farm.

Prior to seeding the aerobic basins, 45 days (equivalent to the HRT in the anaerobic basins based on the daily flow of 1.85 m^3) were allowed to pass to ensure the replacement of the contents of the anaerobic basins with manure.

During this stage two operational regimes were tested for the aeration basins. The first regime started from November 16th and continued to February 7th, 2000. This period will be designated as Step A in this report. The second regime started February 7th and continued to March 10th, 2000 and will be noted as Step B.

Step A - On November 16th, 1999, the three aerobic basins were seeded. The seed was a mixture of activated sludge and primary sludge shipped to the farm from the South-End Water Pollution Control Center. The quantity of seed to each basin was approximately ½ of the basin volume. Mixed Liquor suspended solids averaged 3120 mg/L. All three aerobic basins were aerated providing a dissolved oxygen concentration in the range of 0.4 to 0.7 mg/L. No sludge was recycled from the settling basins to the aeration basins. The effluent, approximately 1.85 m^3/d, was totally returned to the barn to provide adequate dilution of defecate manure.

The operational conditions during Step A are summarized in Table 4.1. Figure 4.1 shows is a flow chart of the treatment system during Step A.

Step B – To improve aerobic treatment efficiency, on February 7th, 2000, the air flow to the first aeration basin was discontinued. This basin then became a flow-through basin. This was done to improve the aeration rate in the two remaining aeration basins and increase their dissolved oxygen concentration. The remaining basins were also re-seeded with fresh activated sludge from the secondary settling tank of the Selkirk Wastewater Treatment Plant. Re-seeding was done to ensure the presence of a sufficient concentration of viable aerobic microorganisms in the aeration basins.

The seed used in Step A was shipped from a sludge storage tank in South-End Water Pollution Control Center. The daily sludge production in this center is kept in the storage tank for a period of at least 12 hrs prior to shipment to another center to be treated. During this storage period the aerobic bacteria are under highly stressed environmental conditions due to the presence of organic matter (primary sludge) and the absence of oxygen. As a result the concentration of aerobic bacteria and their viability in the seed used in step A could be questionable. A change in the source of seed was undertaken to enhance aerobic treatment performance. Furthermore, to maintain a sufficient concentration of microorganisms, the sludge was recycled from the settling basins to the aeration basins.

The operational conditions and the flow chart for Step B are presented in Table 4.1 and Figure 4.2, respectively.

4.1.4 **Stage IV:** Continuous Operation, High Organic Loading
(March 10th to April 6th, 2000)

During this stage the system was loaded with all the manure produced in the barn. The organic loading rate to the anaerobic basins averaged 2.25 kg COD-Tot./m^3-d with a resulting load (F/M) of 0.11 d^{-1} for the aerobic biomass. The average daily flow rate to the treatment system was 4 m^3/d. The treated effluent was partially (about 1.8 m^3/d) discharged to the existing storage tank, and the remaining 2.2 m^3/d was returned to the barn. The returned effluent in this stage was higher than previous stages (1.85 m^3/d). The increase was done to enhance flush out of the defecated manure in the barn.

Table 4.1 presents the operational parameters for this stage of operation. The related flow chart is shown in Figure 4.3.

Table 4.1: Average Operational Conditions During Stage III (Steps A and B) and Stage IV.

Operational Parameters	Stage III		Stage IV
	Step A	Step B	
Ave. daily flow rate (m^3/d)	1.85	1.85	4.0
Ave. temp. of raw manure	13	11	14
No. of anaerobic basins	6	6	6
Volume of anaerobic basins (m^3)	78	78	78
HRT in anaerobic basins (d)	42	42	19.5
Ave. organic loading rate to anaerobic basins (kg COD-Tot./m^3-d)	1.45	1.73	2.25
Ave. temp. in the 1st anaerobic basin (º C)	20	21	21
Ave. temp. in other anaerobic basins (º C)	18.5	18.5	19
No. of aerobic basins	3	2	2
Volume of aerobic basins (m^3)	48.4	32	32
HRT in the aerobic basins (d)	26	17.3	8.0
Source of sludge (seed)	mixture of primary and activated sludge	activated sludge	no seeding
Ave. temp. in the aerobic basins (º C)	17	16	18
Ave. MLSS in the aerobic basins (mg/L)	3120	3393	8162
Ave. MLVSS in the aerobic basins (mg/L)	2383	2673	5467
Ave. F/M ratio (d^{-1}) *	0.10	0.13	0.11
Ave. F/M ratio in the 1st aerobic basin	0.29	0.25	0.22
Ave. range of DO concentration (mg/L)	0.4-0.7	0.9-1.2	0.7-0.9
Sludge recycle ratio (Recycled sludge volume/Influent Volume)	not practiced	1.5	0.5
Ave. returned effluent to the barn (m^3/d)	1.85	1.85	2.2

* F/M = Food to Microorganisms ratio presented as (kg COD-Sol./kg of MLVSS-d)

Figure 4.1: Process Flow Chart During Low Loading Period (Stage III - Step A)

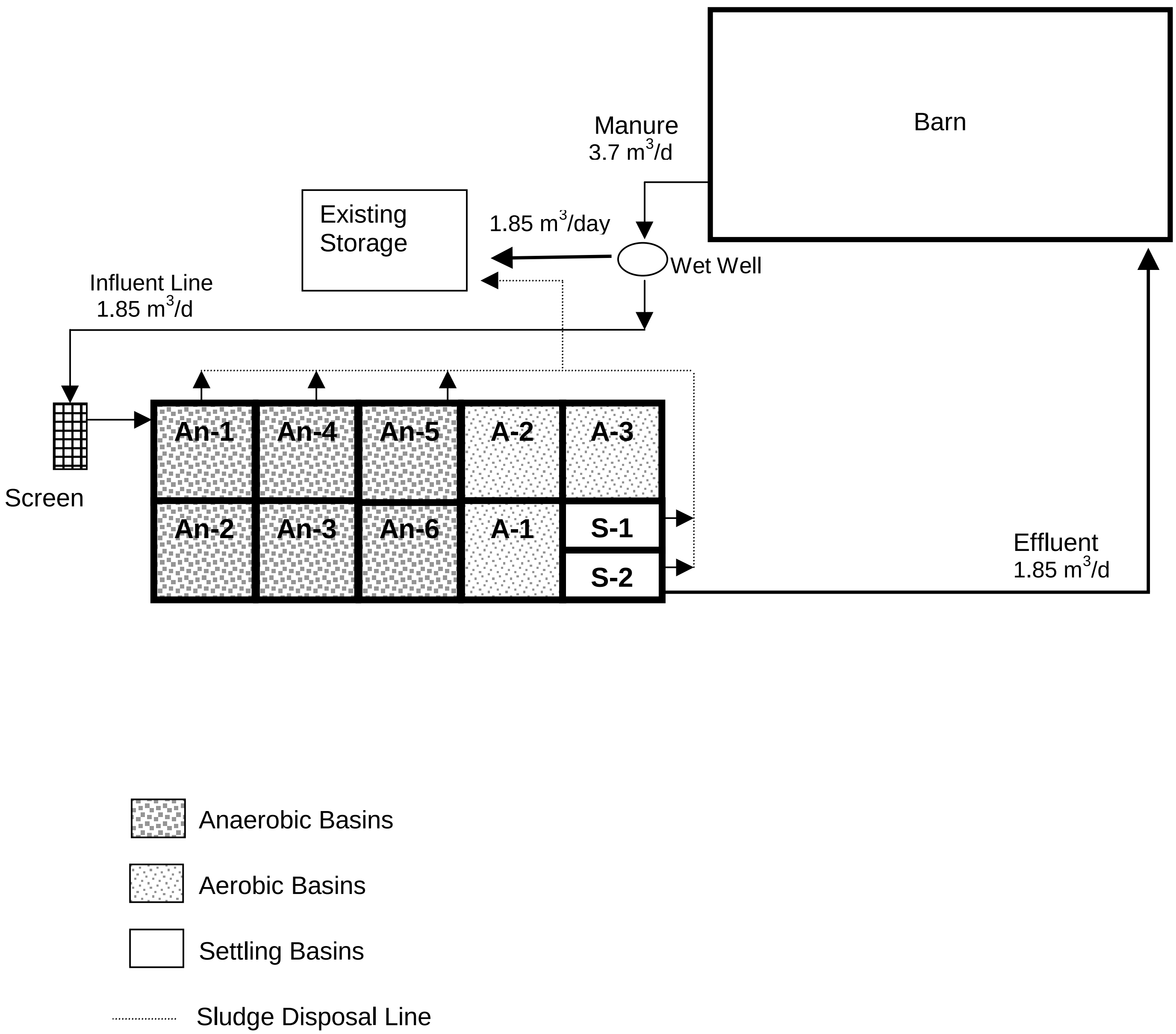


Figure 4.2: Process Flow Chart During Low Loading Period (Stage III - Step B)

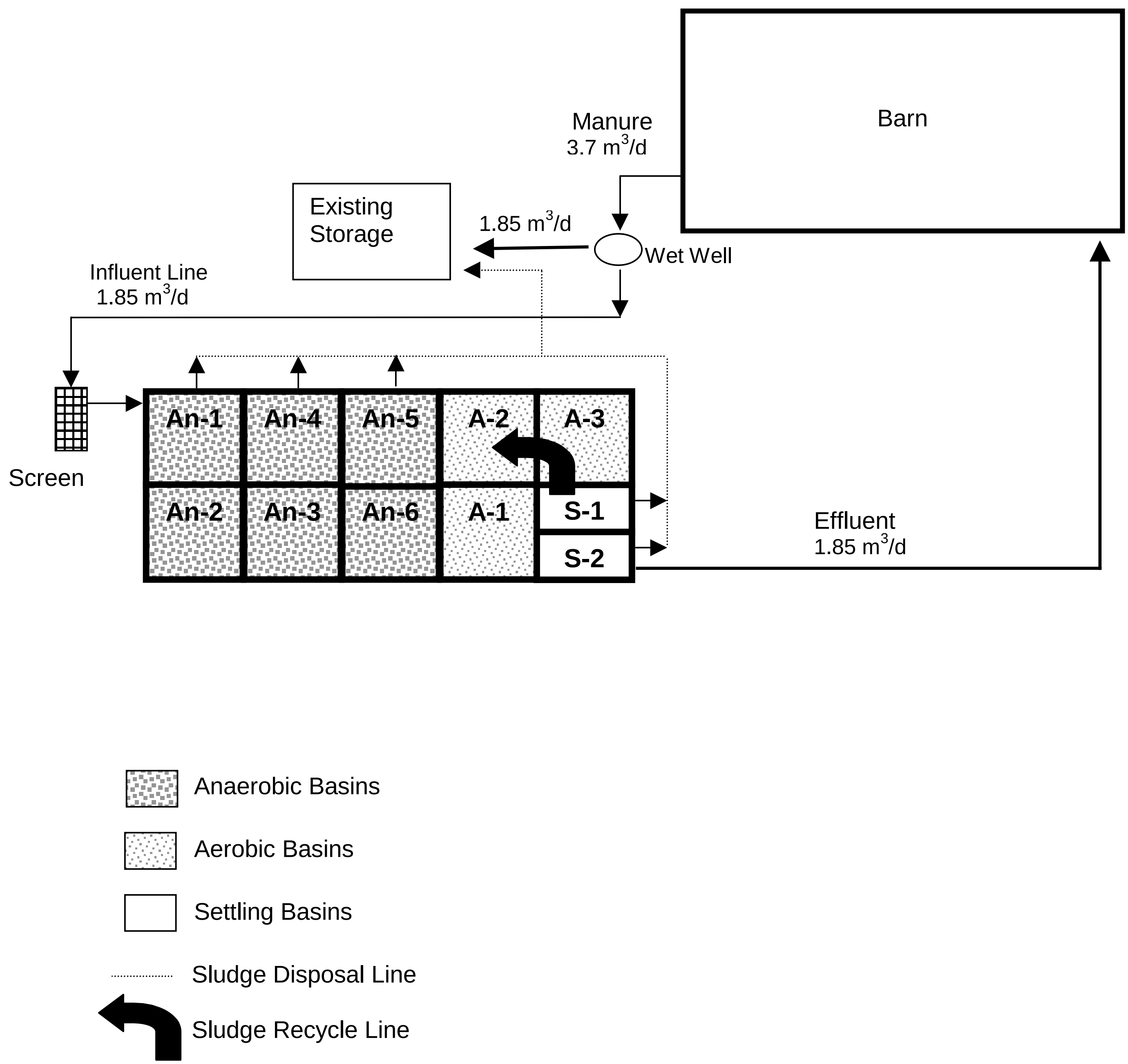
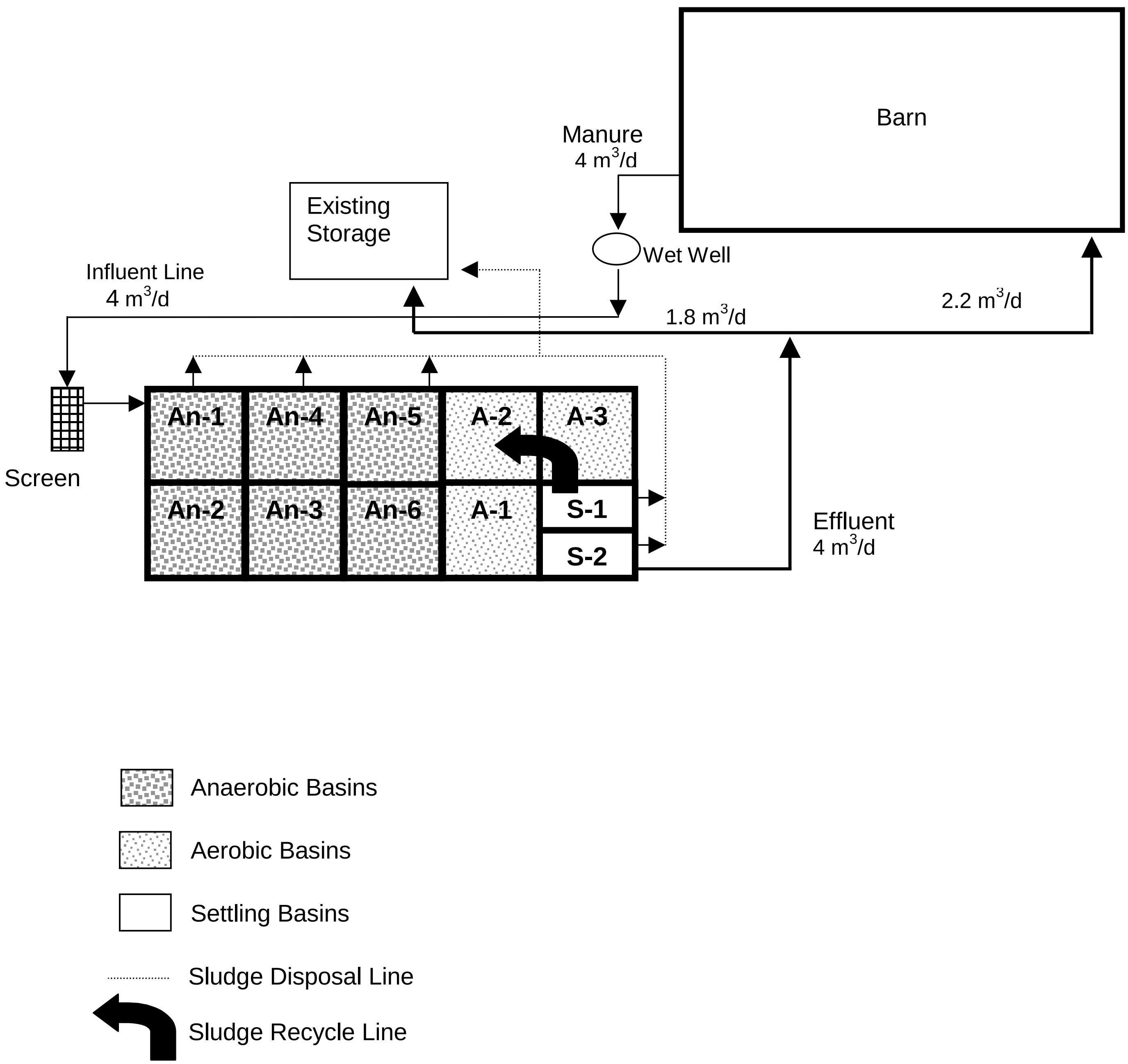


Figure 4.3: Process Flow Chart During High Loading Period (Stage IV)



Chapter 5

RESULTS AND DISCUSSION

The data collected during the different stages of the pilot plant demonstration are outlined in details in Appendix A. The following section includes the analysis of this data and a discussion of these results.

5.1 Operational Temperature

The temperatures of manure, different operational units and the temperature within the building where the pilot plant was located are summarized in Table 5.1.

The average temperature of raw manure (measured in samples taken from the influent line to the treatment system) ranged from 10 to 14 ºC with an average of 13 ºC. A heater installed in the wet well prevented manure from freezing during winter months. The average temperature within the building where the pilot plant located was 24 ºC ranging from 21 to 27 ºC. Two heaters controlled the temperature of the building for winter months.

The anaerobic digestion occurred under psychrophilic condition. The average temperature of anaerobic basins ranged from 18 ºC to 21 ºC. The temperature of the first anaerobic basin where the heating system was installed averaged 21 ºC. However, in the following anaerobic basins, average temperatures were between 18 to 19 ºC.

The temperature of the aerobic basins varied in the range of 15 to 18 ºC with an average of 17 ºC during the course of operation. The settling tanks had temperatures similar to the aeration basins.

5.2 Characteristics of Raw Manure

The average characteristics of the manure (without and with dilution) are shown in Table 5.2. Considerable variation in manure composition was observed, as was expected. Manure is composed of undigested feed, wasted feed and the compounds produced in the gastro-intestinal of the animals (EPRI Report, 1997) and its composition is affected by growth stages of the animals and feed rations.

The total chemical oxygen demand (COD-Tot.), total nitrogen content (TKN-Tot.) and total phosphorous (PO_4-P-Tot.) in this manure averaged 106683 mg/L, 8396 mg/L, and 983 mg/L respectively. Approximately 74% of total nitrogen in undiluted manure and 69% of total nitrogen in diluted manure was composed of ammonia nitrogen. The remaining total nitrogen was in organic form.

The total solids (TS) content of the manure averaged 12.3% (varied in the range of 11.6 to 13.4%) when dillution was not practiced. Dillution reduced total solids percentage to a range of 4.5 to 7.6% with an average of 6.2%. About 69 to 83% of the total solids in manure were composed of organic matter (as indicated by total volatile solids, TVS) with the averages of

70.8% and 81.6% in undiluted and diluted manure. The remaining 17 to 31% of the total solids were inorganic material.

Raw manure pH ranged from 7.2 to 8.3 during the course of study with an average of 7.6 for undiluted manure and 7.4 when dilution was applied.

One of the most important factors affecting the performance of the anaerobic digestion process is the amount of alkalinity present in the waste. Sufficient alkalinity should be present to ensure that the pH will not drop below 6.2 in the digesters (Tchobanoglous and Burton, 1991). The undiluted manure used in this study had an average total alkalinity of 22912 mg/L (as $CaCO_3$) composed of 13800 mg/l in the form of bicarbonate alkalinity (measured to end point pH of 5.1). Under diluted condition, the manure had an average of 11306 mg/l total alkalinity with a bicarbonate alkalinity averaging 7270 mg/L.

The manure was partially fermented in the barn as indicated in Table 5.2 by relatively high concentrations of volatile fatty acids (VFA); 15858 mg/L and 7289 mg/L undiluted and diluted manure. Acetic acid was the primary constituent of volatile fatty acids (average of 62.7% in undiluted manure and 58.7% in diluted manure) followed by propionic and butyric acids, comprising a total average of 31 to 35.3% for the undiluted and diluted manure, respectively. The remaining percentage of volatile fatty acids was composed of Iso and Nano-valeric acids. Acetic and propionic acids are mainly produced during acid fermentation of carbohydrates. The presence of propionic, butyric and valeric acids are the indication of the fermentation of lipids and proteins.

Table 5.2: Characteristics of Raw Manure.

Parameters	**Non-Diluted Manure** (Feb. 16-99 to Apr. 22-99)	**Diluted Manure** (May 20-99 to April 6, 2000)
pH	7.6	7.4
Alka. Total (as Ca CO_3)	22912	11306
TS (%)	12.3	6.2
TVS (as % of TS)	70.8	81.6
COD-Sol.	31567	12411
COD-Tot.	106683	71900
NH_3-N	6240	2953
TKN-Sol.	6750	3050
TKN-Tot.	8396	4269
PO_4-P-Sol.	505	1016
PO_4-P-Tot.	983	1311
VFA	15858	7289
Acetic Acid (as % of VFA)	62.7	58.7
Propionic Acid (as % of VFA)	15.8	20.8
Buteric Acids (as % of VFA)	15.2	14.5

* Measurements are in (mg/L) except pH and where otherwise indicated.

5.3 Stage I

Acclimation of anaerobic microorganisms occurred during this stage (December to Early May, 1999). The system was batch-fed (once every 10 days) with unscreened undiluted manure at an average loading rate in the range of 0.4 to 0.6 kg COD-Tot./m^3-d for the first anaerobic basin which resulted in an average loading of 0.15 to 0.2 kg COD-Tot./m^3-d for the total anaerobic system. This low range of loading was selected to prevent the potential of acid built up within the system. The anaerobic basins, operating in series with manure flowing through a sequence of six basins, represented a plug-flow type system. In a plug-flow reactor configuration, when used for strong waste, the inlet region is a critical zone because it receives the highest organic load. Caution should be taken to prevent overloading of this zone, since the buildup and accumulation of volatile fatty acids could occur if the system is overloaded. This will result in significant reduction of bicarbonate alkalinity and a drop in pH. If the acids concentrations (H_2CO_3 and volatile fatty acids) exceed the available alkalinity, the reactor will sour (a drop in pH), severely inhibiting microbial activity.

The average environmental conditions in the anaerobic basins of the most critical factors, pH and alkalinity, are shown in Table 5.3. The average pH of anaerobic basins were in the range of 7.3 to 7.6. The pH of the aqueous environment should be in the range of 6.6 to 7.6 (Tchobanoglous and Burton, 1991). The optimum range is reported to be between 7.0 and 7.2 (McCarty P.L. 1964). Bicarbonate alkalinity of the basins averaged in the range of 3145 mg/L to 4660 mg/L as $CaCO_3$. This provided sufficient alkalinity and ensured that the pH did not drop below 7.3. Bicarbonate alkalinity in the range of 2500 to 5000 mg/L provides a safe buffering capacity (EPRI Report, 1997).

Table 5.3: pH and Alkalinity of the Anaerobic Basins During Stage I of Operation.

Parameters	An-1 and An-2	An-3 and An-4	An-5 and An-6
pH	7.4	7.6	7.3
Total alkalinity (mg/l as $CaCO_3$)	5550	3807	3635
Bicarbonate Alkalinity (mg/l as $CaCO_3$)*	4660	3277	3145

* End point pH of 5.1.

The performance of the anaerobic bacteria during this stage was evaluated on the basis of the removal of organic matter (as indicated by reduction in COD-Tot.) and volatile fatty acids as shown in Table 5.4. Approximately 95% of total and soluble COD and 98% of volatile fatty acids were reduced within the first and second anaerobic basins during this period. Dilution of raw manure with the content of the anaerobic basins (seed) was a factor in the observed reduction in concentrations of COD and VFA, however, the extent of reductions was much higher than could be related to dilution. Microbial activity played an important role in the removal of organic matter in this manure.

The accumulation of biogas under the covers of the basins was not observed. Analysis of the gas samples taken from the head-space of the anaerobic basins showed average methane and carbon dioxide contents in the range of 3 to 7% and 3 to 4%, respectively. The remaining 89 to 94% of the head-space gas content was oxygen leakage of air to the head-space.

Table 5.4: Performance of Anaerobic Basins During Start-up and Acclimation of Microorganisms

Parameters	Raw Manure	An-2	An-4	An-6
COD-Tot. (mg/l)	106683	4582	2025	-
COD-Sol. (mg/l)	31567	1623	1155	-
VFA (mg/l)	15858	195	<50	<10

5.4 Stage II

This stage of operation (early May to September, 99), as described in details in Section 4.1.2, consisted of trouble shooting and fine-tuning. The system was batch-fed during this phase of operation. The feeding schedule was similar to Stage I; once every 10 days. The organic loading, however, increased to 0.2 to 0.25 kg COD/m^3-d.

Due to the difficulties and relative operational un-stability of the system during this stage, sampling and sample analysis was reduced to a minimum required to ensure suitability of the environmental conditions for the anaerobic bacteria. Measurements were limited to temperature, pH, alkalinity. The temperatures of the anaerobic basins remained in the range of 19 to 21º C. The pH of the first two basins averaged 7.7. Total alkalinity within these basins showed an average of 9598 mg/L with bicarbonate alkalinity averaging 8233 mg/L. Corresponding average concentrations of total and bicarbonate alkalinity in the third and fourth basins were 5425 mg/L and 4805 mg/L.

The observed increase in alkalinity of the anaerobic basins (especially the first two basins), as compared to Stage I, could be the result of many factors including the increased organic loading rate, higher alkalinity in the manure, and/or higher rates of conversion of organic nitrogen to ammonia. Unfortunately, due to reasons indicated before, the number of samples was very limited for this stage. As a result, the actual causes of higher alkalinity and the relative importance of the factors involved cannot be discussed further.

5.5 Stage III – Continuous Operation, Low Organic Loading Rate

This stage of demonstration lasted for a period of 5 1/2 months from late September 99 to March 10th, 2000. The treatment system was fed with half of the total manure produced in the barn at a daily flow rate of approximately 1.85 m^3/d and the organic loading rate to the anaerobic basins was in the range of 1.2 to 2.1 kg COD-Tot./m^3-d. The operational conditions of the anaerobic basins were not changed during this period. The aerobic portion of the system (start-up on November 16th 1999), however, performed under two sets of operational conditions described as Steps A and B in Section 4.1.3. The duration of Step A was almost 3 months from November 16th, 1999 to February 7th, 2000 which then was followed by Step B for a period of one month; February 7th to March 10th, 2000. The differences in the operational conditions of these steps are summarized in Table 4.1 with the related flow charts outlined by Figures 4.1 and 4.2.

The following sections will present, in sequence, the performance of: a) the anaerobic basins over the total period of Stage III, b) the treatment system during Step A, and c) the treatment system during Step B.

5.5.1 Performance of Anaerobic Basins During Stage III

The average treatment results obtained for the anaerobic basins in Stage III are shown in Table 5.5 with treatment efficiencies summarized in Table 5.6. The data presented in these tables are the average of 5 sets of data points.

The data in Table 5.5 indicate that the total nitrogen content in raw manure averaged 3990 mg/L, of which 66.4% was ammonia-N and the rest was organic nitrogen. The manure organic matter measured an average of 81540 mg/L in terms of total COD with the soluble portion being 12880 mg/L or 17% of total COD. The average total and soluble phosphorus contents in manure were 1363 mg/L and 1075 mg/L during this period of study. The presence of VFA in raw manure (7485 mg/l) indicated that manure was already partially fermented. Approximately 57% of VFA in raw manure was acetic acid. The other components of VFA were propionic acid (20%), butyric acid (15%) and valeric acid (8%).

Solid-liquid separation on an average reduced about 19% of the total COD, 8% of the total TKN and 10% of the total phosphorous (measured as PO_4-P), decreasing their concentrations to 66060 mg/L, 3690mg/L, and 1230 mg/L, respectively in the screened manure (influent line) to the anaerobic basins. It was assumed that the solid-liquid separation did not affect the soluble constituents of manure. Thus the concentrations of the soluble parameters such as alkalinity, soluble COD, ammonia nitrogen, soluble TKN, soluble phosphorous, VFA and its constituents in the screened manure remains the same as in raw manure.

The pH of the anaerobic basins remained in the range of 7.2 to 7.6, suitable for anaerobic microbial activity. A reduction in alkalinity, however, was observed. This was most likely due to the volatile fatty acids and carbon dioxide produced during decomposition of organic matter. Carbon dioxide becomes dissolved in the liquid, producing the weak carbonic acid, which, together with volatile fatty acids, will decrease alkalinity. Alkalinity provides the buffer capacity and prevents a decrease in pH.

The six anaerobic basins with a total volume of 78 m^3 provided a HRT of 42 days in the temperature range of 19-21 ºC for the digestion of screened manure. As shown in Table 5.6, the effluent from the sixth anaerobic basin (An-6) had 53% less soluble COD and 81% less total COD than the screened manure entering the anaerobic basins. The reduction in both ammonia and soluble nitrogen in the anaerobic basins was 27% and total nitrogen removal was 41%. A reduction of 86% in total phosphorous was observed as the result of the anaerobic process.

The major mechanisms responsible for the reduction of manure constituents during anaerobic digestion include: settling of the particulate matter, hydrolysis of insoluble organic compounds, decomposition of soluble complex compounds and their conversion to microbial biomass (assimilation) and to gases or volatilized compounds that escape the system. The relative importance of these removal mechanisms and their contribution in total treatment efficiencies cannot be assessed as sludge production was not measured and an analysis of biogas composition was not undertaken. The presence of methane forming bacteria was assessed, however, using lab-scale anaerobic reactors. Samples from the 2nd and 4th anaerobic basins were kept in sealed lab-scale reactors at room temperature (20 ºC). Gas production and composition were measured over a period of one week. The presence of approximately 25% methane in the reactors' head -space gas was an indication of the presence of the methanogens within the anaerobic basins of the pilot plant.

The data in Table 5.6 also indicates that the majority of the anaerobic treatment occurred in the first two anaerobic basins (72% out of 81% removal of total COD, 31% out of 41% removal of total nitrogen, and 81% out of 86% removal of total phosphorous). The treatment efficiencies, especially in the 5th and 6th anaerobic basins, were minimal. Removal of total COD in the 3rd and 4th anaerobic basins increased 5% and only 2% in the 5th and 6th basins. The removal of total nitrogen increased by 7% in the 3rd and 4th basins and 3% in the 5th and 6th basins. Total phosphorous removal was increased by 5% as the waste passed through the last four anaerobic units. These results indicate that, under the implemented operational conditions, three to four anaerobic basins providing a HRT in the range of 21 to 28 days would most likely be adequate to remove approximately 75% of total COD and about 35% of total nitrogen.

The last column in Table 5.6 shows the overall treatment efficiencies of the solid/liquid separation and the anaerobic treatment. The final effluent from the anaerobic process was compared to the raw manure in calculating these efficiencies. A combination of solid/liquid separation and anaerobic process, as indicated in Table 5.6, removed an average of 85% of total COD, 46% of total nitrogen and about 88% of total phosphorous.

Table 5.5: Characteristics of Raw Manure, Screened Manure, and Effluents from the Anaerobic Basins During Stage III; Low Organic Loading Period.
(September 99 to March 10th, 2000)

Parameters	Raw Manure	Screened Manure	Effluent An-2	Effluent An-4	Effluent An-6
pH	7.3	-	7.2	7.4	7.6
Alkalinity, total (as $CaCO_3$)	10806	-	8514	7604	7676
COD-Sol.	12880	-	8320	7480	6080
COD-Tot.	81540	66060	18220	13900	12380
NH_3-N	2650	-	2088	2000	1918
TKN-Sol.	2730	-	2128	2024	1988
TKN-Tot.	3990	3690	2558	2282	2160
PO_4-P-Sol.	1075	-	203	219	160
PO_4-P-Tot.	1363	1230	231	247	167
VFA	7485	-	4746	4322	3632
Acetic Acid (as % of VFA)	57	-	57	62	61
Propionic Acid (% of VFA)	20	-	27	26	32
Butyric Acid (% of VFA)	15	-	9	5	3

* Measurements are in (mg/L) except pH and where otherwise indicated.

Table 5.6: Treatment Efficiencies of Screen and Anaerobic Basins Under Low Organic Loading Rate

Parameters	Screen* % Reduction	An-2** % Reduction	An-4** % Reduction	An-6** %Reduction	Overall*** % Reduction
COD-Sol.	-	35	42	53	53
COD-Tot.	19	72	79	81	85
TKN-Sol.	-	22	26	27	27
TKN-Tot.	8	31	38	41	46
PO_4-P-Tot.	10	81	80	86	88

* % reduction as compared to raw manure
** % reduction as compared to the screened manure
*** % reduction of the final effluent from the anaerobic basins, as compared to the raw manure

5.5.2 Complete System Performance, Stage III-Step A

During this period of operation, November 16th, 1999 to February 7th, 2000, all three aerobic basins were part of the total treatment system and provided a HRT of 26 days. A mixture of primary and activated sludge was used as the initial seeding material. The aeration kept the dissolved oxygen concentrations of the basins within the range of 0.4 to 0.7 mg/L. Sludge recycling from the settling basins to the aeration basins was not practiced. The effluent from the anaerobic basins provided an average organic load (F/M ratio) of 0.1 kg COD-Sol./kg of MLVSS-d to the aerobic system as a whole, and 0.29 kg COD-Sol./kg of MLVSS-d to the first aerobic basin. The final effluent from the pilot plant, approximately 1.85 m^3/d, was totally returned to the barn to provide for the dilution of defecate manure.

The performance of the treatment system components are shown in detail in Table 5.7. This table presents the change in manure characteristics as it passes through the screening, anaerobic process, aerobic process and the settling tanks. The column designated by An-6 shows the characteristics of the effluent from the last (6th) anaerobic basins. The columns A-1, A-2 and A-3 present the effluent characteristics from aerobic basins 1, 2, and 3 respectively. The last column of Table 5.7 is representative of the effluent discharging from the last settling tank.

The system performance measured in terms of percent removal is depicted in Table 5.8. An average removal of 58% in soluble COD resulted from the combination of anaerobic and aerobic treatment of the raw manure. However, soluble COD removal was 48% in the anaerobic basins as compared to 10 to 13% removal in the aerobic basins. The efficiency was practically negligible in the first aerobic basin where the maximum organic load was received. In an efficient aerobic treatment process, the microorganisms use the dissolved easily biodegradable organic fraction of the waste within the first few hours. A high concentration of VFA (2803 mg/l) remained in the effluent from the aerobic basins following a HRT of 26 days, indicating that these basins were not performing efficiently. The low treatment efficiency could have resulted from several factors.

a) Low dissolved oxygen concentration in the basins (0.4 to 0.7 mg/l). The dissolved oxygen concentration is recommended to be above 1 to 2 mg/L in the aeration tanks to ensure a sufficient supply of DO for microbial activity.

b) Low biomass activity due to the type and quality of the seed material. The seed used in this step, as discussed in Section 4.1.3, was of doubtful quality due to its high organic content (primary sludge) and its storage conditions prior to the shipment to the pilot-plant.

c) Non-biodegradability of the organic compounds. Aerobic treatment is limited to the more reactive organic components of the slurry. There remains a relatively inert fraction mainly composed of insoluble material. This can account for up to 70% of the total organic load as indicated by chemical oxygen demand (COD) and is largely unaffected over the short treatment period of less than five days (Burton, 1997).

The average reduction efficiencies in ammonia and soluble TKN following aerobic treatment were 36 and 37%, respectively. Anaerobic treatment was accounted for 27% ammonia removal and 29% removal of soluble TKN. Ammonia and soluble TKN were further reduced by an average of 9 and 8% during aerobic treatment. Ammonia volatilization and biomass assimilation are most likely responsible for the nitrogen reduction.

In general there are three principal mechanisms for the removal of nitrogen: assimilation in biomass, ammonia volatilization and nitrification-denitrification. Because nitrogen is a nutrient, bacteria present in the treatment process will assimilate ammonia nitrogen and incorporate it into cell mass.

Ammonia nitrogen exists in aqueous solution as either the ammonium ion or ammonia, depending on the pH of the solution, in accordance with the following equilibrium reaction (Metcalf & Eddy, 1991):

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$$

At pH levels above 7, the equilibrium is displaced to the left and ammonia is predominant which then can be volatilized. However, at pH levels below 7, the ammonium ion becomes the predominant form. The pH of anaerobic basins (7.2-7.6) and aerobic basins (8.3-8.5), both were in favor of the ammonia form and its volatilization. Aeration also encourages ammonia volatilization. In the absence of nitrification, large ammonia losses are likely, particularly if air flow rates are excessive (Bicudo J., 1999).

Major nitrogen loss through nitrification-denitrification was unlikely due to the low oxygen concentration in the aerobic basins. Dissolved oxygen concentrations above 1 mg/l are essential for nitrification to occur. If DO levels drop below this value, oxygen becomes the limiting nutrient and nitrification slows or ceases (Mecalf & Eddy, 1991). Analysis of the samples taken from the aeration basins did not show presence of nitrite and nitrate at any time. However, simultaneous nitrification-denitrification within the sludge flocs could have happened.

Overall system treatment efficiencies are shown in the last column of Table 5.8. Solid/liquid separation, anaerobic and aerobic treatment followed by settling reduced total COD by 89% and total nitrogen by 52% as compared to the raw manure.

Table 5.7: Performance* of the Treatment System Components.
(Stage III – Step A)

Parameters	Raw Manure	Screened Manure	Effluent An-6	Effluent A-1	Effluent A-2	Effluent A-3	Discharge Effluent
pH	7.2	-	7.6	8.3	8.5	8.5	8.4
Alka. Total (as $CaCO_3$)	9930	-	7250	7157	6600	6653	6497
COD-Sol.	11867	-	6150	6047	4667	4933	4550
COD-Tot.	82033	61400	12233	11700	10117	9733	8633
NH_3-N	2467	-	1797	-	1585	1583	1500
TKN-Sol.	2567	-	1830	-	1640	1627	1575
TKN-Tot.	3750	3433	2050	-	1915	1893	1800
PO_4-P-Sol.	1040	-	140	-	-	-	-
PO_4-P-Tot.	1397	1263	137	-	-	-	-
VFA	7684	-	4203	-	-	2803	-

* Measurements are in (mg/L) except pH and where otherwise indicated.

Table 5.8: Performance Efficiencies of the Treatment System Components.
(Stage III – Step A)

Parameters	Screen* % Reduction	An-6 % Reduction	A-1 % Reduction	A-2 %Reduction	A-3 %Reduction	Overall*** % Reduction
COD-Sol.	-	48*	49*	61*	58*	62
COD-Tot.	25	80**	81**	84**	84**	89
NH_3-N	-	27*	-	36*	36*	39
TKN-Sol.	-	29*	-	36*	37*	39
TKN-Tot.	8	40**	-	44**	45**	52
PO_4-P-Tot.	10	89**	-	-	-	-

* % Reduction as compared to raw manure
** % Reduction as compared to the screened manure (Influent to anaerobic basins)
*** % Reduction as the final system effluent is compared to the raw manure

5.5.3 Complete System Performance, Stage III-Step B

This stage of operation started February 7th and lasted to March 10th, 2000. The operational conditions of the anaerobic basins during this stage were kept similar to Step A. Raw manure was fed to the system with an average daily flow rate of 1.85 m^3. This generated an average organic loading rate of 1.73 kg COD-Tot./m^3-d for the anaerobic basins.

The major operational changes during this stage were applied to the aerobic basins to improve their performance. These changes were as follows:

- The aeration to the first aeration basin was shut-off. This increased the intensity of the aeration in the remaining two aerobic basins and caused a higher concentration of the dissolved oxygen. The DO in these basins increased to between 0.9 and 1.2 mg/L. The aeration basin provided a HRT of 17 days. The first aerobic basin was then used as a pass-through basin for the waste.

- The aeration basins were seeded with a good quality activated sludge shipped directly from the secondary settling tank of the Selkirk Wastewater Treatment Plant. This was done to ensure the presence of a viable population of aerobic microorganism in the basins.

- A portion of the settled sludge in the settling tanks was recycled to the aeration basins to maintain a high concentration of the microorganisms. The recycle ratio was 1.5.

The effluent from the last anaerobic basin provided an F/M ratio of 0.25 kg COD-Sol./kg of MLVSS-d to the first aerated basin and an average F/M ratio of 0.13 kg COD-Sol./kg of MLVSS-d to the aerobic basins as a system. The details of the operational conditions for Step B are summarized in Table 4.1. The related flow chart is shown in Figure 4.2.

Table 5.9 is similar to Table 5.8, presenting the changes in manure characteristics as it passed through the different components of the treatment system. The performance efficiencies of solid/liquid separation, anaerobic basins, aerobic basins and settling basins for this stage of operation are indicted in Table 5.10.

Comparison of the raw manure characteristics between Stages A and B, shows that the manure was stronger during Step B with respect to the soluble COD, soluble nitrogen and phosphorous. Regardless of this, a reduction efficiency of 91% in soluble COD was achieved as a result of anaerobic and aerobic treatment. The percent reduction in soluble COD within the aerobic basins was improved to 30% as compared to the 10% reduction that occurred during Step A.

Ammonia and soluble TKN reduction in the anaerobic and aerobic basins averaged approximately 66%. Approximately 28% of ammonia and 25% of the soluble TKN were removed during anaerobic treatment. The remaining 37% reduction in ammonia and 41% reduction in soluble TKN occurred within the aerobic basins. The removal of these components in the aerobic basins during Step A was in the range of 8 to 9%.

These results indicate that the changes made in the operational conditions of the aerobic system improved the performance of the aeration basins significantly. Moreover, the very low concentration of VFA (75 mg/l) in the effluent of the last aerobic basin confirms the treatment enhancement.

The overall system treatment efficiencies during Step B are shown in the last column of Table 5.10. The treatment system provided an average total COD removal of 98% and an average total TKN removal of 77% during this stage of operation as compared to 89% and 52% achieved respectively during Stage A. The removal mechanisms of the manure constituents during this step are similar to those discussed in the previous sections.

Table 5.9: Performance* of the Treatment System Components.
(Stage III – Step B)

Parameters	Raw Manure	Screened Manure	Effluent An-6	Effluent A-2	Effluent A-3	System Effluent
pH	7.3	-	7.6	8.3	8.4	8.5
Alka. Total (as $CaCO_3$)	12120	-	8315	4635	3795	3625
COD-Sol.	14400	-	5975	1625	1235	1335
COD-Tot.	80800	73050	12600	4225	3575	1805
NH_3-N	2925	-	2100	-	1010	875
TKN-Sol.	2975	-	2225	-	1010	890
TKN-Tot.	4350	4075	2325	-	1165	1000
PO_4-P-Sol.	1110	-	179	-	-	-
PO_4-P-Tot.	1375	-	213	-	-	-
VFA	7185	-	2775	-	75	-

* Measurements are in (mg/L) except pH and where otherwise indicated.

Table 5.10: Performance Efficiencies of the Treatment System Components.
(Stage III – Step B)

Parameters	Screen* % Reduction	An-6 % Reduction	A-2 %Reduction	A-3 %Reduction	Overall*** % Reduction
COD-Sol.	-	59*	89*	91*	91
COD-Tot.	10	83**	94**	95**	98
NH_3-N		28*		66*	69
TKN-Sol.	-	25*	-	66*	70
TKN-Tot.	6	43**	-	71**	77
PO_4-P-Tot.	-	84*	-	-	-

* % Reduction as compared to raw manure
** % Reduction as compared to the screened manure (Influent to anaerobic basins)
*** % Reduction as the final system effluent is compared to the raw manure

5.6 Stage IV – Continuous Operation, High Organic Loading Rate

This stage, March 10th to April 6th, 2000, was the continuation of the work in Step-B, however with a higher load.

During this stage the treatment system was fed with the total load of manure produced in the barn. The average daily flow rate to the treatment system was 4 m^3/d. This created a HRT of 19.5 days in the anaerobic portion of the treatment and 8 days in the aerated basins. The average temperature within the anaerobic basins ranged from 18 to 22ºC and in the aerobic basins was 18 ºC. The treated effluent was partially (about 1.8 m^3/d) discharged to the existing storage tank, and the remaining 2.2 m^3/d was returned to the barn. The returned effluent was higher than previous stages to enhance flush out of the defecated manure in the barn. The organic loading rate to the anaerobic basins during this stage averaged 2.25 kg COD-Tot./m^3-d. The effluent from the anaerobic treatment process produced an average F/M ratio of 0.11 COD-Sol./kg of MLVSS-d for both aerated basins and a F/M ratio of 0.22 COD-Sol./kg of MLVSS-d for the first aerated basin. Dissolved oxygen concentrations in these basins ranged between 0.7 and 0.9 mg/L. The settled sludge was recycled to the aerated basins with a recycle ratio of 0.5.

The operational conditions of this stage are presented in Table 4.1 with the flow chart shown in Figure 4.3.

5.6.1 Performance of Anaerobic Basins During Stage IV

The characteristics in the anaerobic basins under high load conditions are shown in Table 5.11, followed by treatment efficiencies in Table 5.12.

The data in Table 5.11 indicate that the total nitrogen content in raw manure averaged 4733 mg/l, of which 73% was ammonia-N and the rest was soluble and particulate organic nitrogen. The manure organic matter measured in terms of total COD, averaged 60900 mg/L with approximately 18% (11233 mg/l) being soluble fraction. The manure total and soluble phosphorous averaged 1183 mg/l and 937 mg/l respectively. Partial fermentation of manure occurred in the barn as indicated by a considerable concentration of volatile fatty acids (6343 mg/L). Component analysis of VFA showed 61% acetic acid, 21% propionic acid, 13% butyric, and 5% valeric acid.

Solid-liquid separation on an average reduced total COD by 28% and total TKN by 4%, decreasing their concentrations to 43867 mg/l and 4550 mg/l, respectively, in the effluent from the screening device. Screening does not affect manure soluble constituents, thereby alkalinity and other soluble parameters of the screened manure were assumed to be the same as raw manure.

A decrease of 0.3 to 0.5 units of pH occurred within the anaerobic basins. However, the average pH of these basins (7.3–7.5) was appropriate for anaerobic microorganisms. A decrease in alkalinity of manure was observed as it passed through the anaerobic treatment process. This reduction as mentioned in previous sections is the result of VFA and carbon dioxide production. Carbon dioxide can dissolve in liquid and produce carbonic acid. The remaining alkalinity in all the basins, however, was adequate to provide a good buffer capacity and prevent drastic drops in pH.

The anaerobic process reduced the organic matter, nitrogen and phosphorus contents of the manure. Removals were most likely due to mechanisms such as settling, biomass assimilation, and conversion to gases and volatile compounds.

The removal efficiencies in the anaerobic basins were not the same in all the basins. Comparison of the effluent characteristics of the anaerobic basins (Table 5.11), reveals that the treatment of manure practically occurred within the first four basins. The last two anaerobic basins did not contribute to the reduction of manure compositions. Rather, due to the long HRT and solubilization and degradation of sludge, an increase in the concentrations of all constituents (except phosphorous) was observed in the effluent of these basins (A-6). This is also reflected in Table 5.12, where treatment efficiencies in terms of percent reduction of constituents increased gradually up to the fourth anaerobic basin (An-4) and then decreases in the following basins (An-6).

The removal of soluble and total COD in the first two anaerobic basins were in the order of 26% and 48%. An additional decrease of 32% in soluble COD and 27% in total COD occurred within the 3rd and 4th anaerobic basins. The 5th and 6th anaerobic basins decreased treatment efficiency of soluble COD removal by 3% because of the release of soluble organic matter in these basins. These basins did not affect total COD removal.

Ammonia and soluble TKN removal averaged about 20% in the first two basins, which increased to an additional 29% within the 3rd and 4th basins. The decrease in total TKN was 16% in the first two basins and 39% in the second two basins provided for a total percent removal of 55% within these four basins. The efficiencies of nitrogen removal in different forms declined considerably in the last two anaerobic basins. As indicated in Table 5.12, the removal efficiencies of ammonia and soluble nitrogen reduced to about 35% and for total TKN the removal efficiency reduced to 44%.

In general, the data and results point out that the anaerobic system of the pilot plant has been over designed for a 300 head feeder barn. Under the operational conditions tested, a design with a HRT of 10 to 12 days would result in treatment efficiencies similar to those obtained with a HRT of 19.5 days.

The last column in Table 5.12 shows the overall treatment efficiencies during this stage of operation. As a result of solid/liquid separation and anaerobic treatment process, an average removal of 84% for total COD, 46% for total nitrogen and about 79% for total phosphorous were achieved. These efficiencies are very similar to the efficiencies obtained during low organic loading period (Stage III), indicating that the high organic loading did not deteriorate the performance of the anaerobic basins, a sign of the system stability.

Table 5.11: Characteristics of Raw Manure, Screened Manure, and Effluents from the Anaerobic Basins During Stage IV: High Organic Loading Period. (March 10 to April 6th 2000)

Parameters	Raw Manure	Screened Manure	Effluent An-2	Effluent An-4	Effluent An-6
pH	7.8	-	7.3	7.4	7.5
Alka. Total (as Ca CO_3)	12507	-	9583	6803	8113
COD-Sol.	11233	-	8313	4733	5013
COD-Tot.	60900	43867	22633	11100	10800
NH_3-N	3457	-	2763	1767	2247
TKN-Sol.	3583	-	2830	1833	2297
TKN-Tot.	4733	4550	3807	2033	2543
PO_4-P-Sol.	937	-	583	273	203
PO_4-P-Tot.	1183	-	627	290	253
VFA	6343	-	4210	2638	2953
Acetic Acid (as % of VFA)	61	-	53	56	60
Propionic Acid (% of VFA)	21	-	33	35	33
Butyric Acid (% of VFA)	13	-	7	3.5	3.5

* Measurements are in (mg/l) except pH and where otherwise indicated.

Table 5.12: Treatment Efficiencies of Screen and Anaerobic Basins Under High Organic Loading Rate.

Parameters	Screen* % Reduction	An-2 % Reduction	An-4 % Reduction	An-6 %Reduction	Overall % Reduction
COD-Sol.	-	26*	58*	55*	55
COD-Tot.	28*	48**	75**	75**	84
NH_3-N	-	20*	49*	35*	35
TKN-Sol.	-	21*	49*	36*	36
TKN-Tot.	4*	16**	55**	44**	46
PO_4-P-Tot.	-	47*	75*	79*	79

* % Reduction as compared to raw manure
** % Reduction as compared to the screened manure
*** % Reduction as the final effluent from anaerobic basins is compared to the raw manure

5.6.2 Complete System Performance During Stage IV

The changes in manure during all processes in Stage 4 are shown in Table 5.13. In addition, the removal efficiencies for some of the parameters such as COD, nitrogen and phosphorous are summarized in Table 5.14.

The aerobic basins were not very efficient during this stage of operation. An average reduction of 55% in soluble COD achieved within the anaerobic basins. In comparison, soluble COD during aerobic treatment was reduced by 11% (compared to 30% removal during Stage III, Step B). A similar situation was observed with nitrogen, with 35 to 36% removal of ammonia and soluble nitrogen in the anaerobic basins and 2 to 3% removal in the aerobic basins. The reduction efficiency of COD by aerobic process in this stage resembles the efficiency obtained in Stage III, Step A. Soluble COD removal efficiency during Step A was in the range of 10 to 13%. A high concentration of VFA (1290 mg/L) in the final effluent of the treatment plant is also an indication of inefficiency of the aerobic process.

Since the F/M ratio of the aerobic basins during this stage was similar to the F/M ratio applied during Step B, the reason for the low efficiency cannot be related to the higher loading rate. The reasons for lower efficiencies could be: a) lower DO concentration, b) shorter HRT, and c) less active biomass.

The average dissolved oxygen concentration in the aerobic basins was 0.7 to 0.9 mg/L as compared to 0.9 to 1.2 mg/L observed in Step B. The hydraulic retention time was also shorter during this stage (8 days) as compared to 17.3 days in step B. However, 8 days HRT should be adequate if other conditions are suitable. The other possible factor for the low efficiency could be low activity of the microbial population. The sludge from the settling tanks was not removed often. Therefore the recycled sludge to the aerobic basins could have been composed of an aged microbial biomass with a low level of activity.

The overall system treatment efficiencies during Stage IV are shown in the last column of Table 5.14. The average treatment system efficiencies were 90% for total COD, 48% for total TKN and 90% for total phosphorous. These are very similar to the efficiencies obtained during Step A of the operation.

Table 5.13: Performance of the Treatment System Components.
(Stage IV)

Parameters	Raw Manure	Screened Manure	Effluent An-6	Effluent A-2	Effluent A-3	System Effluent
pH	7.8	-	7.5	8.6	8.6	8.6
Alka. Total (as $CaCO_3$)	12507	-	8113	8683	8127	7837
TS	47733	37000	9167	-	-	7867
TVS	38300	27433	5200	-	-	4633
COD-Sol.	11233	-	5013	4583	3767	2967
COD-Tot.	60900	43867	10800	12600	12433	6967
NH_3-N	3457	-	2247	-	2180	2113
TKN-Sol.	3583	-	2297	-	2197	2167
TKN-Tot.	4733	4550	2543	-	2593	2450
PO_4-P-Sol.	937	-	203	-	-	95
PO_4-P-Tot.	1183	-	253	-	-	113
VFA	6343	-	2953	-	-	1290

* Measurements are in (mg/l) except pH and where otherwise indicated.

Table 5.14: Performance Efficiencies of the Treatment System Components.
(Stage IV)

Parameters	Screen* % Reduction	Anaerobic** % Reduction	A-2** %Reduction	A-3** %Reduction	Overall*** % Reduction
COD-Sol.	-	55*	59*	66*	74
COD-Tot.	28	75**	71**	72**	90
NH_3-N	-	35*	-	37*	39
TKN-Sol.	-	36*	-	39*	40
TKN-Tot.	4	44**	-	43**	48
PO_4-P-Tot.	-	79*	-	-	90

* % Reduction as compared to raw manure
** % Reduction as compared to the screened manure (Influent to anaerobic basins)
*** % Reduction as the final system effluent is compared to the raw manure

5.7 Overall View

5.7.1 Screen Performance

The screen device used in this treatment system required dilution of the manure in order to operate properly. Manure as defecated in the barn was too thick for this separator to function. Dilution was provided by recycling of the treated effluent to the barn. Nevertheless occasional clogging of the screen was possible and required careful attention.

The solid-liquid separation provided solids suitable for land disposal or composting. The characteristics of separated solids are shown in Table 5.15.

Table 5.15: Characteristics of the Screened Solids

Date	Moisture Content (as wet Wt.%)	Total Dry Solids (as wet Wt.%)	Total Volatile Solids (TS%)
18-Jan-00	83.0	17.0	93.4
1-Feb-00	77.0	23.0	94.4
22-Feb-00	76.0	24.0	93.4
23-March-00	76.5	23.5	93.0
31-Mach-00	80.5	19.5	95.4
6-April-00	73.4	26.6	92.0
Average	78.4	22.3	93.6

The performance of the screen in removing of total solids, total COD and total nitrogen varied considerably depending mainly upon manure thickness and manure flow rate. The percent removal of total solids and total COD fluctuated in the range of 16 to 37 percent and 8 to 36%. For total TKN, the range of removal was 3 to over 10%. The removal efficiencies reported for stationary screens with an opening of 1 mm used for hog manure were 6 to 31% for total solids, 0 to 32 % for COD and 3 to 6% for total TKN (Zhang and Westerman, 1997).

Chapter 6

ECONOMIC ANALYSIS OF TREATMENT OPTIONS

Introduction

The value of the technologies discussed in this report will depend on their ability to reduce the COD and the costs that are required to establish and operate the system. It has already been concluded that the anaerobic system provided the greatest reduction in COD, the manure separator and the aerobic system were least effective at reducing COD. This section will focus on the costs required to construct and operate a treatment system for a 5000 head feeder barn that includes one or more of treatment system components in order to determine the most cost-effective approach. The same treatment system would accommodate a farrow to finish farm of 700 sows. Four building options will be discussed using a specific combination of the three treatment system components. Building floor plans for each option are included in appendix B.

6.1 Option I – Manure Separator / Anaerobic / Aerobic Treatment System

Option 1 is all-inclusive, using all three system components to treat the manure. It is similar in many respects to the pilot project, however the key difference is that it is designed for a much larger operation and the size of each component has been adjusted based on our observations in this project. The building is divided into two areas. One area includes anaerobic, aerobic and manure separation and the other area is designed to provide temporary storage for the separated solids.

Due to the scale of operation and our cold weather climate, the size of the building has been increased to accommodate a temporary storage facility for separated solids. The capacity of the storage would be large enough to store three to four months of solids. The walls of the building are 18 feet high to accommodate the removal of solids in storage by a farm tractor, bobcat or commercial front-end loader.

The second stage of treatment involves the anaerobic digestion of manure. It requires four storage basins with a capacity of 21,120 cubic feet for manure storage. From prototype studies Table 5.6 (p.32), it is apparent that most of the treatment was occurring in the first 14 days of storage. Therefore, the anaerobic basins were designed for a hydraulic retention time of 14 days. This reduces the capital cost of the building significantly since fewer basins need to be constructed.

The aerobic treatment system includes two basins with a storage capacity of 10,560 cubic feet (hydraulic retention time of 7 days), blowers, aerobic heads, and an air line. The pilot project demonstrated the inefficiency of this system in reducing COD. The capital cost therefore is very high in relation to the amount of treatment it is able to achieve.

The capital cost of Option I is $269,000 (Table 6.1) while the annual energy cost is $19,300 (Table 6.2). The total annual cost that includes depreciation and interest, maintenance and repair, labor, solids removal, and energy is $51,500 (Table 6.2). A summary of the unit costs used in this analysis is presented in Appendix A.

Table 6.1: Capital Costs

Costs	Option 1	Option 2	Option 3	Option 4
Building Materials & Labor	160,400	137,400	69,400	90,400
Mechanical				
Separator System	35,000	35,000	-	-
Aerobic System	26,000	-	-	-
Plumbing	23,100	21,100	18,100	20,100
Space & Manure Heating	4,500	4,500	4,500	4,500
Mechanical sub-total	88,600	60,600	22,600	24,600
Electrical	20,000	18,000	15,000	15,000
Total Cost	**$269,000**	**$216,000**	**$107,000**	**$130,000**
Cost Per Pig Place	**$53.80**	**$43.20**	**$21.40**	**$26.00**

Notes: Concrete is based on $90/yard
Concrete & Framing labor was determined using $3.75 per square foot
Concrete labor for basin walls was determined using $28 per lineal foot

Table 6.2: Annual Operating Costs

Costs	Option 1	Option 2	Option 3	Option 4
Depreciation & Interest	23,900	19,100	9,300	11,300
Maintenance & Repair	4,000	3,200	1,600	1,900
Labor	1,800	1,500	1,200	1,200
Solids Removal	2,500	2,500	0	0
Energy Cost	19,300	9,000	8,100	8,600
Total Annual Cost	**$51,500**	**$35,300**	**$20,200**	**$23,000**
Cost Per Pig Marketed	**$3.43**	**$2.35**	**$1.35**	**$1.53**

Notes: Depreciation is based on straight-line method over 20 years
Interest is based on 8% annually
Energy costs were based on $0.06/kW.h

6.2 Option II – Manure Separator / Anaerobic Treatment System

Option II is similar in many respects to Option I, however the aerobic system has been removed. The result of this is a reduction in the overall size of the building and the omission of the aerobic equipment. The capital cost of the building and equipment will be $216,000 (Table 6.1) while the total annual cost to operate the system will be $35,300 (Table 6.2).

6.3 Option III – 14-Day HRT Anaerobic Treatment System

Option III is the most basic since it only involves the anaerobic system. It includes only four basins for anaerobic treatment with the same storage capacity as Options I and II. The capital cost of this option would be $107,000 (Table 6.1). The annual cost would be $20,200 (Table 6.2) including depreciation and interest.

6.4 Option IV – 21-Day HRT Anaerobic Treatment System

In order to compensate for the elimination of the manure separator and improve the effectiveness of the anaerobic system, Option III has been modified to include an extra two basins, increasing the hydraulic retention time to 21 days. The total cost of this option would be $130,000 (Table 6.1) and the annual cost would be $23,000 (Table 6.2) including depreciation and interest.

6.5 Discussion

From the above analysis it is clear that the aerobic system has a very high cost in relation to the level of treatment that might be expected. The marginal cost to include the aerobic system (option 1 minus option 2) is $53,000 and the additional annual operating cost is $16,200 for a very limited capacity to reduce COD. The energy to operate the aeration system is a significant component of the annual cost.

The elimination of the separation system reduces the capital cost (option 2 minus option 3) by approximately one half from $216,000 to $107,000. The annual cost savings to eliminate the separation process is approximately $15,100. The separation process produced a COD reduction of approximately twenty percent, therefore option 3, which relies on anaerobic digestion only with a hydraulic retention time of 14 days, would experience a noticeable reduction in overall system performance.

Option 4 includes additional retention capacity to enhance treatment performance. An allowance has also been made in this option for mixing within the cells to further improve the treatment process. The economic analysis indicates that system performance is probably best enhanced through improvement of the anaerobic treatment process.

In order to verify the potential to simplify the three stage treatment system, further investigations are required to determine treatment efficiencies with the separator and aerobic systems removed. Because the treated effluent will be eventually applied to agricultural land for crop production anyway, complete treatment to discharge standards is not necessary. The objective of a manure treatment system should be to stabilize the manure nutrients and to reduce odour potential. The process should be capable of providing liquids of sufficient quality to permit flushing of the barn pits, thereby reducing barn odour production and enhancing air quality.

Chapter 7

CONCLUSIONS

Overall system efficiency averaged 98 percent removal of total COD at the low organic load rate (approximately one half of manure from the 300 head feeder barn). At the high organic load rate, overall efficiency averaged 84 percent removal of total COD. Total Kjedhal nitrogen was reduced 77 percent at the low loading rate and 46 percent at the high loading rate.

These treatment efficiencies produced an effluent that could not be discharged into surface watercourses. The effluent, however, was very effective for flushing the barn and produced a noticeable improvement in the barn air quality. The level of treatment achieved should result in dramatic reductions in odour during storage and land application as compared to untreated manure. In addition, the reduction in nitrogen and phosphorous will result in a significant reduction in the land base required for disposal.

The treatment system did not achieve the levels of efficiency reported in Taiwan. Reasons for this are likely due to the differences in temperature (greater than 25°C in Taiwan versus 15 to 21°C in the pilot plant). In addition, considerably more water is used in Taiwan (20-30L/pig-day) than in Canada (7 L/pig-day) and this could impact performance.

The greatest amount of treatment occurred in the anaerobic section of the system (approximately 50 to 75 percent reduction in total COD). The solid-liquid separator reduced total COD by 10 to 30 percent and the aerobic section reduced total COD by up to approximately 10 percent. Of the three components, the anaerobic process is considerable simpler, less costly and easier to operate. The mechanical components are much reduced in the anaerobic section.

The anaerobic basins were very stable and changes in operational conditions did not upset their performance. Particularly during the start-up and trouble-shooting stages, the loading rate was very non-uniform, however this appeared to have relatively little impact on the anaerobic basins. In comparison, the aerobic basins were much more sensitive to changes in operational conditions.

The solid-liquid separator worked well after the manure was diluted to approximately six percent solids. The separator provided solid manure with an average moisture content of 78 percent. For optimum composting, some mixing with drier organic matter would be required.

The treatment efficiency in the aerobic section was low. This may have been due to low dissolved oxygen levels or the biomass activity was lower than expected. The recycled sludge to the aerobic basins may have been composed of an aged microbial population due to insufficient sludge removal from the settling tanks. The reduction in total COD was greatest during Stage III-B (low loading rate, two aeration basins). Dissolved oxygen levels were highest during this phase.

Both the anaerobic and aerobic sections appeared to be overdesigned in terms of volume and hydraulic retention time. At the low loading rate, most of the reduction in COD in the anaerobic basins took place in the first two of six basins. The hydraulic retention time in these first two basins was 14 days. Similarly, at the high loading rate, four anaerobic basins, representing a hydraulic retention time of 13 days, were sufficient to achieve most of the COD reduction that occurred in the anaerobic section.

The aerobic section was most efficient during Stage III-B. During this phase the majority of COD reduction occurred in the first of the two aerobic basins. The hydraulic retention time on each of these aerobic basins was eight days.

Very little biogas production was observed under the covers of the anaerobic basins, therefore gas production was not measured. The presence of methane formers was confirmed, however, the reason for the low gas production has not been determined.

An economic analysis of treatment options for a large scale hog operation indicated that elimination of the aerobic and separation system components will dramatically reduce costs with only a limited potential impact on performance. Further evaluation is required to confirm the range of treatment possible with only the anaerobic system.

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