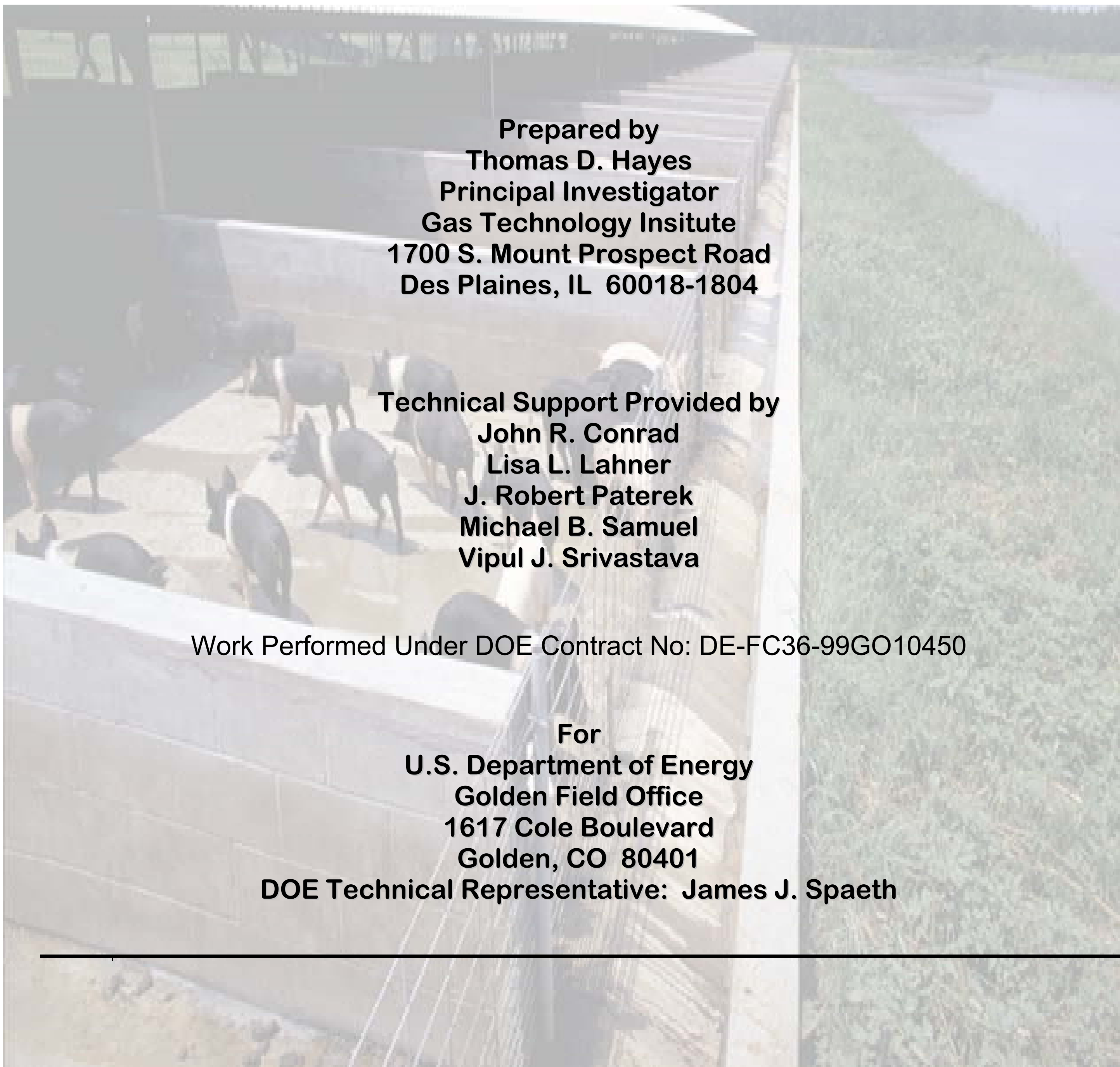
ECONOMICALLY AND ENVIRONMENTALLY FRIENDLY PRODUCTION OF FUEL AND POWER FROM HOG MANURE USING GTI'S HIMET^{SM} TWO-STAGE ANAEROBIC DIGESTION TECHNOLOGY

FINAL TECHNICAL REPORT



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Abstract

Manure management is an ever-increasing environmental impact problem within the U.S. livestock industry due to the trends in growing scale of operation of individual animal raising facilities. Anaerobic digestion, the fermentation of organic matter into a mixture of methane and carbon dioxide called biogas, offers the livestock industry a viable solution to this problem. When anaerobic digestion is combined with by-product recovery and biogas utilization, the integrated system can potentially solve manure handling issues while creating significant energy, environmental and economic opportunities. The overall objective of this project was to conduct a laboratory proof-of-concept evaluation to determine the potential energy generation and pathogen control benefits of applying anaerobic digestion for the management of swine manure.

Under this project, GTI has advanced the application of anaerobic digestion with the successful laboratory demonstration of GTI's HIMET^{SM} two-phase anaerobic digestion technology within the swine industry. Obtained from an underfloor storage tank, swine manure (at about 4.1% total solids) was fed to laboratory-scale combined-phase and HIMET^{SM} two-phase digester units at a loading of approximately 2.4 ± 0.1 g/liter-day and at a hydraulic retention time (HRT) of 15 days. In parallel, sewage sludge (about 5.5% total solids) was fed at a loading rate of 2.9 g/liter-day to the same types of digesters (15 days HRT) that served as controls for the experiment. Results showed that: 1) HIMET^{SM} achieved 10-15 percent greater methane yield per pound of volatile solids fed to the digester, reaching an average methane yield of 6.2 ft3/lb VS added (0.39 liters/gram VS added); 2) HIMET^{SM} achieved an organics-to-methane conversion efficiency of 80 percent versus 68 percent for conventional digestion; 3) HIMET^{SM} achieved consistently high biogas heating values of over 700 Btu/ft^3; 4) Mesophilic and thermophilic designs of HIMET^{SM} were able to achieve greater than 99.5 percent reductions in pathogen indicator organisms, sufficient to potentially comply with Class A biosolids classification guidelines; and, 5) Manure feedstock is a more easily convertible feedstock than sewage sludge, yielding about 50 percent more methane yield per dry pound of feed.

A preliminary economic analysis indicates that a HIMET^{SM} digester design, utilizing simplified, farm-compatible materials, can produce biogas for half the cost incurred with conventional anaerobic digestion. Deployed on a 10,000 head swine operation, HIMET^{SM} could produce biogas at a levelized cost of approximately \$3.50/GJ (assuming the performance of the full scale unit was comparable to that of the laboratory unit) versus a projected cost of

about \$7.40/GJ for conventional digestion. In the HIMET^{SM} process, roughly 4 metric tons of manure volatile solids in 105 m^3 of manure slurry per day would be processed to produce about 60 GJ/day of biogas energy; using a high efficiency cogeneration package (38% efficiency for converting biogas to electricity), this amount of biogas would be sufficient to support a 0.25 MW generator.

Based on the results of this project, the HIMET^{SM} technology is ready for pilot and full scale testing at large swine facilities. The HIMET^{SM} technology is expected to facilitate the capability of anaerobic digestion to provide an economical source of biogas that can support a substantial future source of distributed electricity generation. On the national stage, anaerobic digestion can potentially provide substantial amounts of energy from livestock wastes. The total manure that is generated in the US exceeds 300 million dry metric tons per year (counting wastes from cattle, poultry and swine operations). If a third of this manure can be captured and if average conversion efficiencies of 65% (equivalent of 0.3 m^3 methane/dry kg) can be achieved, nearly 1.0 EJ per year of renewable methane energy can be produced, amounting to about 5% of the US natural gas demand. If all of this methane is converted to electricity at 38% efficiency, over 9,000 MW of electricity could be produced.

Glossary of Terms

Acidogenic	Acid Producing
BOD_5	Five-Day Biological Oxygen Demand (Standard Methods, 1998)
C:N	Carbon to Nitrogen Ratio
CAFO	Concentrated Animal Feeding Operation
COD	Chemical Oxygen Demand (Standard Methods, 1998)
CSTR	Continuous Stirred Tank Reactor
FS	Fixed Solids or ash fraction = (TS-VS)
HIMET^{SM}	The two-phase anaerobic digestion process designed for animal waste conversions
HRT	Hydraulic Retention Time
Methanogenic	Methane Producing
OLR	Organic loading rate usually expressed in metric units of kg VS added/m^3 of reactor / day or g VS added/liter of reactor/day
Ortho P	Orthophosphorus = Inorganic Phosphorus (PO_4^{-3} + HPO_4^{-2} + $H_2PO_4^-$ + H_3PO_4)
PF	Plug Flow Digester
PTOW	Publicly Owned Treatment Works (community sewage treatment plant)
TKN	Total Keldahl Nitrogen = Organic Nitrogen + Ammonia
Total P	Total Phosphorus
TS	Total Solids as determined by drying an aliquot of material to a constant weight at 105°C (Standard Methods, 1998)
v/v/d	**v**olume of gas/**v**olume reactor/**d**ay
VS	Volatile Solids or the fraction of the total solids that are volatilized at 550°C in 24 hours

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1.0 Introduction

The growth and concentration of the livestock industry in the United States have posed new challenges and opportunities in the area of animal waste management. On any particular day, there are more than 60 million swine (farrow-to-finish), 9 million dairy animals, 7.7 billion poultry (chickens, commercial broilers and turkeys) and 90 million cattle in confined feeding operations across the U.S. (National Agricultural Statistics, 2001). The manure removal from these operations requires a substantial disposal effort. The annual generation of manure from swine operations alone is more than twice that of human waste biosolids collected at the approximately 16,000 sewage treatment plants in the U.S.

There have been several trends in the nature of hog raising operations that have affected the volumes and the nature of manure streams. The numbers of animals handled in each facility has increased markedly since the 1970s. As shown in Figure 1.1, the average size of a hog operation has increased more than ten times since 1975; there are now six U.S. firms that own more than 100,000 sows (National Agricultural Statistics, 2001). This rapid growth in the average size of hog farms is reflected in the rapid decline in the numbers of hog farms in the U.S. since World War II. The number of hog farms has declined by about 5.7 percent per year from over one million farms in 1967 to less than 75,000 in 2002, though the total inventory of hogs during this period has cycled within a narrow range of 50 million to 62 million hogs.

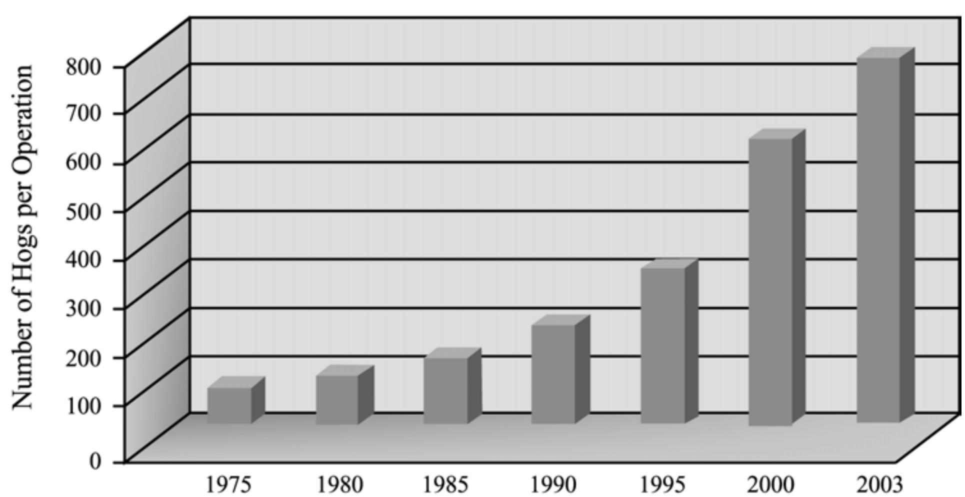

Figure 1.1 U.S. Hog Farm Trends Toward Larger Operations

Another trend that has had a profound effect on the economics of hog farming is the increased use of automation, which has substantially increased the dilution and volumes of manures requiring storage and disposal for swine and dairy operations (ASAE, 1998; MWPS-18, 1993). The growth in facility size and automation have worked together to substantially increase the volumes of manure, often referred to as biosolids, requiring disposal at each livestock facility, thereby increasing the potential impact of each operation on the environment. Average per farm volumes of manure wastes have increased by more than an order of magnitude since the 1960s.

This rapid increase in hog farm waste generation and the heavy reliance on open lagoons for waste storage have raised growing concerns over the potential impact of hog manure on the environment (i.e. surface water runoff, groundwater contamination, pathogens, etc.) and to the public health.

For the modern hog operation, the development of an improved generation of biological anaerobic digestion processing integrated with mechanical systems for automated operation, heat recovery, cooling, and electricity generation could potentially convert an environmental problem into a substantial energy generation opportunity if certain critical development goals can be achieved. In addition, the successful development of this integrated technology could potentially provide multiple benefits of enhanced environmental compliance, significant control of methane emissions and reduced livestock mortality that would result in a large positive economic impact on the livestock industry as a whole.

2.0 Objectives

The overall objective of this study was to conduct a laboratory proof-of-concept evaluation to determine the potential energy and environmental benefits of applying anaerobic digestion for the management of swine manure. Specific objectives of the project were as follows:

- Determine the potential of anaerobic digestion for the production of methane from hog manure feedstocks.
- Compare the performance of GTI's two-phase HIMET^{SM} digestion process with a completely stirred tank reactor (CSTR).
- Evaluate the benefits of anaerobic digestion processing including pathogen control that would reduce the potential for groundwater and surface water contamination.
- Perform a preliminary engineering economic analysis of the application of anaerobic digestion to swine operations.

3.0 Background

3.1 Swine Industry

United States hog production has grown since 1930 by an average of 1.5 percent per year. At roughly 60 million animals in inventory, the U.S. is currently one of the largest swine producers in the world, second only to China with more than 450 million animals in inventory. Pig production is prolific in the U.S., farrowing an average of 8.5 pigs per litter, twice each year. Sows can usually be bred less than a week after weaning and have a gestation period of approximately 114 days. Rapid breeding and high growth rates of swine place pig raising operations among the most efficient means of meat production (Plain, 1997).

A number of improvements have continually boosted efficiencies over the past decades. One advancement has been the placement of pigs indoors, reducing the impact of harsh weather in terms of animal stress and death rates. Quality breeding, gestation and farrowing facilities have led to higher conception rates and lower mortality rates. Segregation of animals during early weaning has reduced the farrowing interval and has reduced losses of young pigs due to crushing. Improved genetics have resulted in a sow herd with greater maternal traits while improving the carcass quality of slaughter hogs.

The modernized swine industry, however, has also increased pressure on hog operations to expand. The cost of space for each hog decreases with larger buildings and in larger animal raising operations. Structural change and specialization have also contributed to the growth in the average size of swine operations. The rapid growth in average numbers of animals per hog raising operation is shown in Figure 1.1. In 1975, the average size of a hog operation was about 74 animals (National Agricultural Statistics, 2001). Since 1975, per farm animal numbers have increased by more than eight percent per year. By 2006, the average size of hog raising facilities is expected to exceed 1,000 hogs.

The principal reason for the rapid growth in swine operations is the specialization and economy of scale that have led to lower production costs and higher profitability of larger operations. The top third of swine operations in size have averaged about 20 percent return on investment (Plain, 1997). Today, six firms own more than 100,000 sows. The combined production from 2,500 of the largest hog operations accounted for half of the U.S. hog inventory in 2000. Approximately 47 percent of hog operations comprise over 10,000 animals each; about 30 percent comprise over 50,000 animals each (National Agricultural Statistics, 2001).

The rapid expansion in average facility size is having a large effect on manures that are generated from each facility and it is expected that the trend in the U.S. will continue — away from small piggeries where feed is grown and wastes are land applied locally, and toward larger operations located in areas that may not be within the traditional "corn belt" and involving the import of grain feedstocks. Swine diets mainly consist of a mixture of high-energy grains such as corn and grain sorghum, with occasional use of wheat, barley and other small grains. Soybean meal is the primary source of protein in swine diets. The addition of animal by-products such as meat and bone meal, feather meal, fish meal, and poultry by-product meal also contribute significant amounts of protein and provide some of the minerals required for maintenance, growth, reproduction and lactation. Human and industrial by-products are also used for swine feeds, including dried bakery products, fats and oils from restaurants that are produced as by-products of cooking food, and other food industry waste products. Due to the simplicity of grains, most feed manufacturers add vitamins and minerals to the swine feeds. A list of typical nutrient requirements for swine production is shown in Table 3.1

In addition to nutrients, swine are also given medicinal additives in their feeds to ensure their growth, maintenance and development. Medicinal feed additives for swine are shown in Table 3.2

Nutrient	Breeding[c]	Lactating[d]
metabolizable energy, kJ/g[2]	13.43	13.43
protein, %	12	13
arginine, %	0.00	0.40
histidine, %	0.15	0.25
isoleucine, %	0.30	0.48
leucine, %	0.30	0.48
lysine, %	0.43	0.60
methionine and cystine, %	0.23	0.36
phenylalanine and tryosine, %	0.45	0.70
threonine, %	0.30	0.43
tryptophan, %	0.09	0.12
valine, %	0.32	0.60
linoleic acid, %	0.1	0.1
calcium, %	0.75	0.75
phosphorus, %		
total	0.60	0.60
available	0.35	0.35
sodium, %	0.15	0.20
chlorine, %	0.12	0.16
magnesium, %	0.04	0.04
potassium, %	0.20	0.20
copper, mg/kg	5	5
iodine, mg/kg	0.14	0.14
iron, mg/kg	80	80
manganese, mg/kg	10	10
selenium, mg/kg	0.15	0.15
zinc, mg/kg	50	50
vitamin A, IU/kg	4000	2000
vitamin D, IU/kg	200	200
vitamin E, IU/kg	22	22
vitamin K, mg/kg	0.5	0.50
biotin, mg/kg	0.20	0.20
choline, g/kg	1.25	1.00
folacin, mg/kg	0.30	0.30
niacin, available, mg/kg	10	10
pantothemic acid, mg/kg	12	12
riboflavin, mg/kg	3. 75	3.75
thiamin, mg/kg	1	1
pyridoxine, mg/kg	1	1
vitamin B_{12}, μg/kg	15	15

Table 3.1 Nutrient requirements of breeding and lactating swine (NRC, 1988)

Medicinal Feed Additives for Swine

Atrophic rhinitis	chlortetracycline
	oxytetracycline
	tylosin
	tylosin/sulfamethazine
Bacterial swine enteritis (scours)	apramycin
	carbadox
	chlortetracycline
	oxytetracycline
Cervical abcesses	chlortetracycline
Colibacillosis	apramycin
	colimix
Dysentery	arsanilic acid
	bacitracin methylene disalicylate
	carbadox
	lincomycin
	roxarsone
	tiamulin
	virginiamycin
Dysentery, vibrionic	carbadox
	oxytetracycline
	tylosin
	tylosin/sulfamethazine
Fly control	rabon
Leptospirosis	chlortetracycline
	oxytetracycline
Mycoplasma pneumonia	lincomycin
Necrotic enteritis	carbadox
	oxytetracycline
Stress	chlortetracycline
Worms, kidney	fenbendazole
	levamisole hydrochloride
Worms, large roundworms	dichlorvos
	fenbendazole
	hygromycin B
	levamisole hydrochloride
	pyrantel tartrate
	thiabendazole
Worms, lungworms	fenbendazole
	levamisole hydrochloride
Worms, nodular	dichlorvos
	fenbendazole
	hygromycin B
	levaimsole hydrochloride
	pyrantel tartrate
Worms, small stomach	fenbendazole
Worms, thick stomach	fenbendazole
Worms, threadworms	levamisole hydrochloride
Worms, whipworms	dichlorvos
	fenbendazole
	hygromycin B

Table 3.2 Examples of medicinal additives for swine feedstocks (NRC,1988)

Among the nutrient additives is copper, a heavy metal that can potentially inhibit digestion if excessive amounts are added to the swine feeds. At the recommended level of 5 mg/kg, digestion operations are not likely to be inhibited based on previous data on the effects and fate of heavy metals in the digestion of sewage sludge (Hayes and Theis, 1978). However, the mistaken addition of copper to levels that exceed 30 mg/kg could be inhibitory and toxic to the digestion process.

Traditional animal raising operations raised pigs from birth to death (farrow-to-finish). The new trends in swine operations involve the separation of feeder pig producers (grown over a 60 day period - up to 18 kg) and feeder pig finishing (grown over a 160 day period - up to 100 kg or larger). The industry average for the weight of animals in confined feeding operations is approximately 61 kg (134 lbs). Manure generation characteristics of swine are shown in Tables 3.3 through 3.6. This information is useful when estimating the possible energy generation via anaerobic digestion, the potential environmental impact, and the capacities and costs of processes required to treat the manure streams.

Parameter	Mean	Std. Dev.
Live Weight, kg	61	---
Total Manure, kg	84	24
Urine, kg	39	4.8
Density, kg/m_3	990	24
Total Solids, kg	11	6.3
Volatile Solids, kg	8.5	0.66
BOD_5, kg	3.1	0.72
COD, kg	8.4	3.7
pH	7.5	0.57
TKN, kg	0.52	0.21
Ammonia-N, kg	0.29	0.10
Total P, kg	0.18	0.10
Ortho-P, kg	0.12	---

Key: wb = Weight Basis
TS = Total Solids
VS = Volatile Solids (organic fraction)
FS = Fixed Solids (inorganic fraction)
TKN Total Keldahl Nitrogen (organic + inorganic)

Table 3.3 Typical body mass and manure production and characteristis per day per 100kg of swine (Day & Funk, 1998)

Parameter	Nursery	Growing	Finishing	Gestation Sow	Sow and Litter	Boar
Size, kg	15.9	29.5	68.1	125	170	159
Manure, kg/day	1.0	1.9	4.4	4.0	14.9	5.0
TS, kg/day	0.091	0.18	0.41	0.36	1.36	0.45
VS, kg/day	0.077	0.14	0.33	0.30	1.09	0.420
BOD_5	0.032	0.059	0.14	0.12	0.45	0.16
N, kg/day	0.007	0.013	0.031	0.028	0.10	0.035
P_2O_5, kg/day	0.005	0.010	0.023	0.022	0.078	0.027
K_2O, kg/.day	0.005	0.11	0.024	0.022	0.082	0.028

Key: BOD_5 = Biological Oxygen Demand
COD = Chemical Oxygen Demand

Table 3.4 Production rates and characteristics of fresh manure by pigs (Zhang & Felmann, 1997)

Component	Farrow	Nursery	Finish	Breeding
Moisture, %	96.5	96.0	91.0	97.0
TS, % w.b.	3.5	4.00	9.00	3.00
VS, % w.b.	2.28	2.79	6.74	1.8
FS, % w.b.	1.22	1.71	2.26	1.20
N, g/L	3.6	4.8	6.3	3.0
NH_4N, g/L	2.8	4.0	---	---
P, g/L	1.8	1.6	2.7	1.2
K, g/L	2.8	1.6	2.2	2.1
C:N Ratio	4	3	6	3

Table 3.5 Swine waste characteristics from under-floor manure storage tanks (USDA, 1992)

	Anaerobic Lagoon		Feedlot *	
Component	Sludge	Supernatant	Settled Sludge	Runoff Water
Moisture, %	92.4	99.8	88.8	98.5
TS, % w.b.	7.60	0.25	11.2	1.5
VS, % w.b.	4.68	0.12	90.7**	---
FS, % w.b.	2.92	0.13	21.3**	---
BOD5, g/L	---	0.40	---	---
COD, g/L	64.6	1.2	---	---
N, g/L	3.0	0.35	5.6**	2.0**
NH_4N, g/L	0.76	0.22	4.5**	1.2**
P, g/L	2.7	0.13	2.2**	0.38**
K, g/L	7.6	0.38	10.0**	1.10**
C:N Ration	8	2	---	---

** Assuming semi-humid climate (76 cm annual rainfall); annual sludge removal*
*** kg/d/1000kg animal weigh;*

Table 3.6 Swine waste characteristics from storage/treatment facilities (Chynoweth et.al, 1998)

On average, each animal produces about 0.35 kg (0.78 lbs) of manure organic matter per day; the generation of total manure solids, including inorganic matter, amounts to 0.40 kg (0.88 lbs) per day. Since 1975, the generation of total manure solids from the average hog raising operation has increased the annual per-site manure production from 10.8 dry metric tons (11.9 dry tons) to over 110 dry metric tons (120 dry tons).

To understand the nature of the swine waste material, it is important to understand the manner in which the waste is handled and stored. Manure collection is achieved with several methods of removal and storage. Manure management systems include: 1) open lot manure management; 2) under-floor manure storage; and, 3) outside storage. In an open lot manure management system as shown below in Figure 3.1, the lots are periodically scraped using front-end loaders, and manure is piled and stored for land spreading. Manure residues in these stockpiles range in consistency from 15 to 30 percent solids. Runoff from each of these piles is usually piped to a liquid waste holding pond. For smaller operations, water runoff from manure piles was routed through a vegetative filter or soil infiltration area in lieu of a lagoon. This method has been one of the most commonly used modes of manure management in the swine industry of the past.

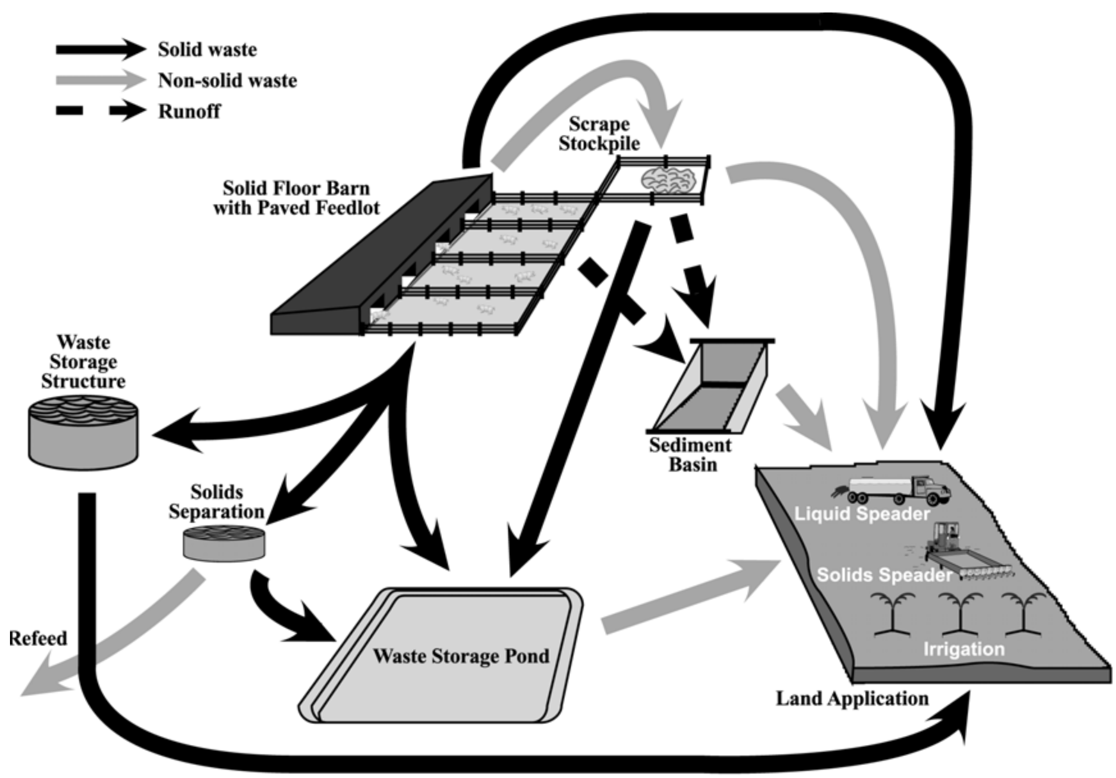

Figure 3.1 Open lot manure management system

Another type of operation incorporates slotted floors in the piggery for manure management as shown in Figure 3.2. A reinforced concrete storage pit is generally positioned under the slotted floor to catch the manure generated by the animals. Manure in these types of pits usually contain four to eight percent solids and is usually in the form of a slurry. When the basin is filled, the manure solids are agitated thoroughly and pumped either to another manure storage structure or taken to a land application operation. Many new facilities are replacing the under-floor storage method with an automated water-flush removal of manure from the floor to a sump that is emptied into a very large lagoon. The push for this type of automation, however, can result in a significant dilution of manures and a further expansion of manure volumes.

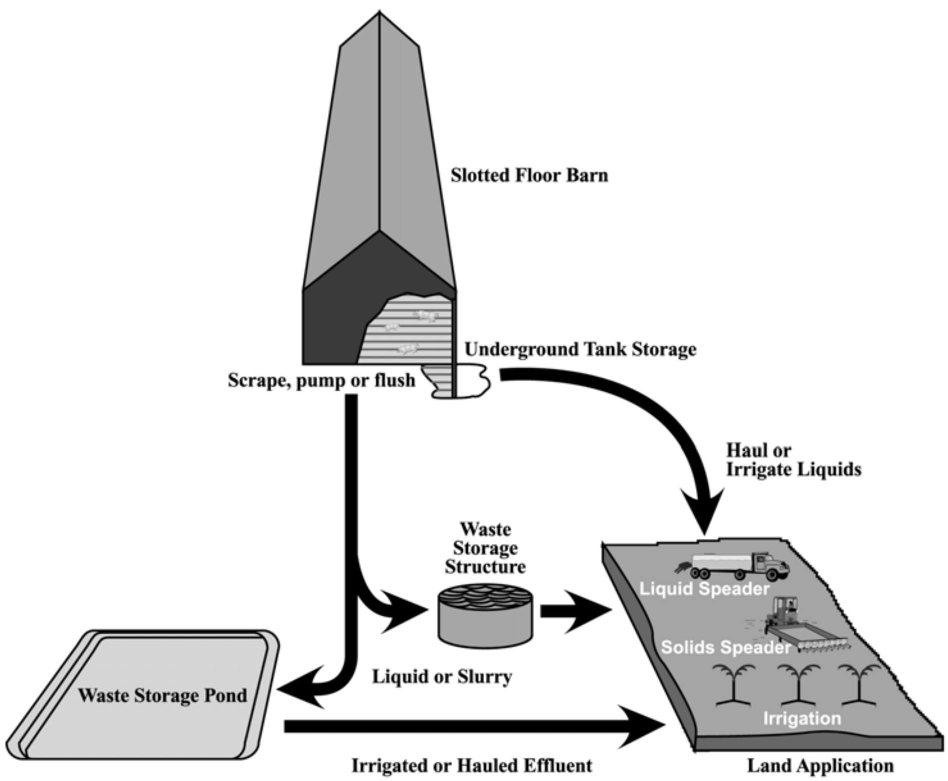

Figure 3.2 Under-floor manure management system

Many of today's new swine operations have shifted from the use of open lot storage of manures of high solids consistency to the handling of manures as dilute slurries that greatly expand manure volumes requiring storage and disposal. On average, the amount of water contained in manures has increased markedly. Prior to 1975, the moisture content of most swine manures varied from 15 to 30 percent because of the wide use of traditional systems for manure collection and storage. The increased use of water flush systems for today's automated manure management produces far more manure volumes from each facility than was produced from each hog farm in the past. This rapid increase in manure volume production increase is illustrated in Figure 3.3. The contemporary hog raising operation with manure consistencies of two to five percent total solids generates annual manure volumes that are 27 to 69 times the volumes of manure generated from the average animal raising operation in the mid-1970's.

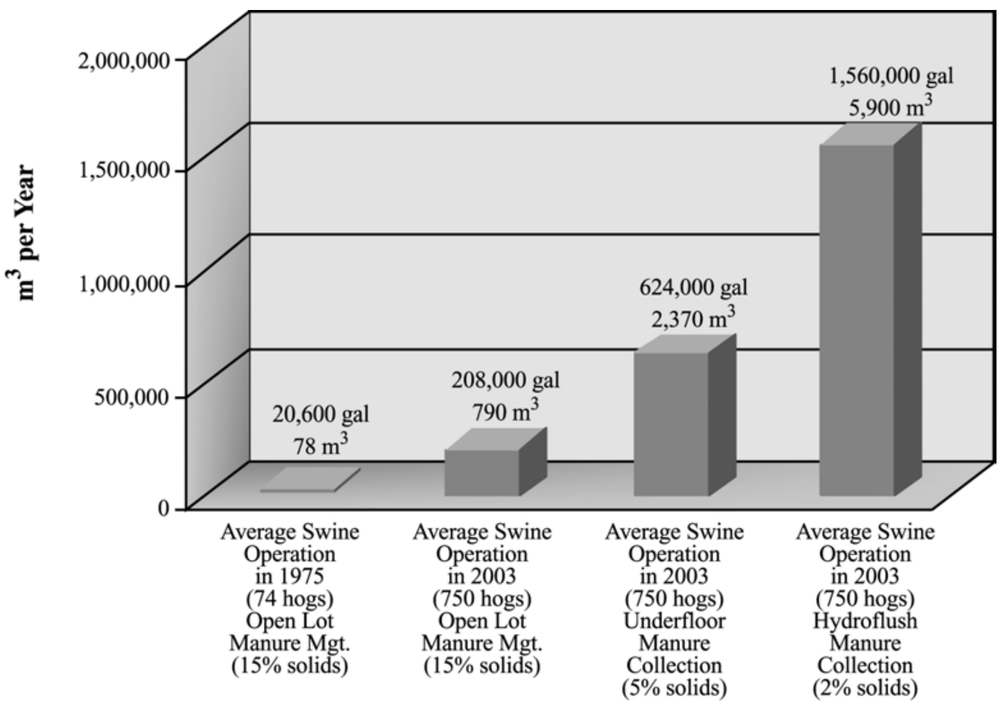

Figure 3.3 Comparison of manure volumes generated from hog operations past and present, and manure volume generated per year

This rapid point-source growth in per-facility manure volume generation is one of the most important reasons for increased concern among state and federal regulators over the potential environmental impact of the swine industry. It is generally recognized that the large volumes of manure wastes at new swine raising operations will require treatment to avoid potential risks to the environment and to the public health (Lusk, 1998; Chynoweth, et al., 1998; Webb, 1998). The daily output of manure from a modest swine operation with 10,000 hogs is equivalent in organic matter generation to an eight million-gallon-per-day municipal sewage treatment plant serving a community of about 80,000 people. At most new facilities, the manure slurries that are generated are so large that they have to be stored in large lagoon systems that are capable of holding millions of gallons of liquid waste for several months. For example, a 10,000 hog operation with a manure stream removed as a five percent slurry would produce a waste volume of approximately 22,500 gallons per day (85 m^3 per day); a six-month storage capacity would require a lagoon with a total volume of about five million gallons (19,000 m^3).

Lagoon systems provide some treatment, but are usually unheated and open to the atmosphere, which prevents efficient anaerobic breakdown of manure solids during storage. During storage, lagoon systems may develop leaks to groundwater or surface water if inadequate liners are used in construction of the basins. Lagoon systems are also subject to overflow during events of excessive rainfall. One of the most disastrous examples of hydraulic overload of lagoons occurred at North Carolina swine raising operations during Hurricane Floyd. In this event, a number of swine lagoons were not able to resist the destruction of Hurricane Floyd; many lagoons overflowed as a result of the flooding that occurred. The results of this event included widespread contamination of surface waters and water supplies with bacteria and organic compounds (Whole Hog, 1999). This disaster called attention to the debate over the concentration of animals at modern facilities and the environmental impact that results from these operations.

In addition, odor issues have become important for large facilities where residential development has placed homes in close proximity to swine operations (Lusk, 1998). Air emissions from concentrated animal feeding operations have also been mentioned as a potential area of concern in USEPA guidelines for these facilities (USEPA, 1999).

There is also growing concern over the impact of manure based methane emissions as a contributor of greenhouse gases affecting global climate change. Fresh manure solids, when generated, contain organic matter that will anaerobically degrade to methane and carbon dioxide when stored and/or disposed of in the field using conventional handling techniques. Under these conditions, up to two to three cubic feet of methane per dry pound of organic solids could ultimately be generated over a one-year period from the manure of livestock amounting to more than 1000 cubic feet of methane emissions per sow. When multiplied times tens of millions of animal units, the uncontrolled methane release from swine manure represents a substantial source of greenhouse gas emissions.

Other environmental impacts associated with conventional swine manure handling methods include attraction of rodents, insects, and other pests; release of animal pathogens; atmospheric methane release; and the release of ammonia nitrogen, phosphorus, and other nutrients to ground and surface waters.

The challenges of most immediate concern, however, are those issues that have substantial impacts on the bottom line in the livestock industry. Historically a very low profit margin industry, the livestock industry is increasingly plagued with problems of economic importance, including:

- Increased water use associated with increased automation of manure handling;
- Growing manure volumes requiring land disposal;
- Increased animal mortality due to on-farm diseases and stresses due to air emissions in confined feeding operations; and,
- Lost opportunities in controlling energy costs associated with general electric power demands, heating and cooling required for animal climate control, and refrigeration needs.

Other than operating labor, these items comprise the most significant cost factors associated with the livestock industry. These considerations underscore the need for economic challenges of the swine industry. The technology evaluated in this report involves the application of anaerobic digestion to the conversion of swine waste to energy with the concomitant treatment of the waste stream to alleviate many of the environmental and community acceptance challenges faced by the swine industry.

3.2 Anaerobic Digestion Technology

Anaerobic digestion is a microbial process in which anaerobic bacteria ferment organic matter (in the complete absence of oxygen) to form products of methane and carbon dioxide (McCarty, P.L., 1964). Anaerobic digestion can also be described as the engineered anaerobic conversion of organic matter to methane and carbon dioxide. Anaerobic digestion is a biological process consisting of at least two stages: 1) the initial breakdown of complex organics by acid forming bacteria to simpler compounds including volatile acids; and, 2) the conversion of volatile acids (such as acetic and propionic) by methanogenic bacteria to a mixture of methane and carbon dioxide called “biogas.” Both steps of the process are usually performed in a single tank; however, in the two-phase digestion process design, each of these steps is separated and optimized for operation in each of two stages placed in series (Ghosh et al., 1975; Chynoweth, et al., 1998). A diagram of the general anaerobic digestion pathway is shown in Figure 3.4.

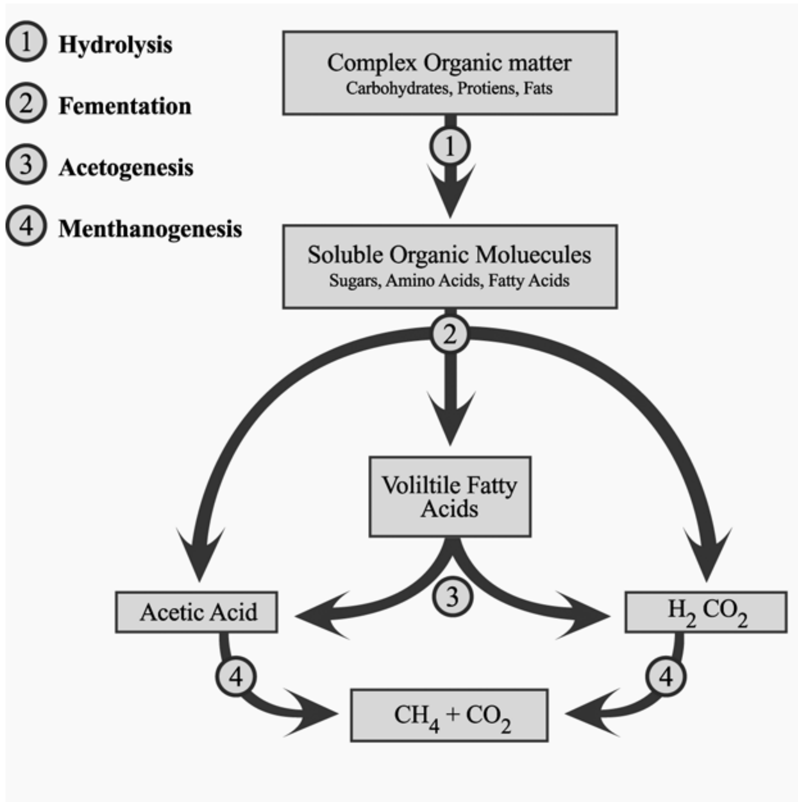

Figure 3.4 Microorganism-mediated transformations in anaerobic digestion

In operation, most anaerobic digestion proceses perform best (with regard to conversion rate and efficiency) at 30–35°C (mesophilic temperature range) or at 50–55°C (thermophilic temperature range). At these temperatures, the digestion process essentially converts organic matter in the presence of water into gaseous energy, which is easily separated from the water fraction within the compartment where methanogenesis occurs.

Most digesters produce biogas containing approximately 60 percent methane and 40 percent carbon dioxide with a Btu value of 600 Btu/ft^3. Since the conversion of manures is conducted at mild temperatures with natural microbial transformations, anaerobic digestion is considered to be among the most environmentally benign of energy generation processes. In the course of converting organic matter into carbon dioxide and methane, the microorganisms (bacteria) that carry out the reactions assimilate nutrients such as nitrogen and phosphorus to reproduce and grow. Thus, some of the ammonia and other nutrients are transformed into cellular material (Speece, 1996).

The stoichiometry of converting organic materials to carbon dioxide and methane is described for anaerobic digestion processing (McCarty, 1964; Andreadakis, 1992). The methane yields depend largely on the composition of the feedstock that is converted. The methane yields for cellulosic feedstocks approximate 0.45 m^3 per kg (or 0.45 liters per gram) of volatile solids converted, while the methane yields for lipid compounds can exceed 0.65 m^3 per kg volatile solids converted. As shown in Table 3.7, the composition of swine manure feedstocks is largely comprised of hemicellulosic, cellulosic feed-stocks, protein and some minor fraction of lipid; based on this composition, the ultimate methane yield for most swine manure residues can be expected to be slightly higher than the conversion yield for cellulose.

	Material	**g/kg of TS**
	Ash	**176**
Organic	Crude Protein	209
	Lipids	77
	Carbohydrates	538
	hemicelluose	(208)
	cellulose*	(229)
	lignin*	(101)

Table 3.7 Compositional analysis of swine manure (Andreadakis, 1992)

3.3 Previous Investigations in Swine Waste Treatment

Most wastestreams generated from swine raising operations contain concentrated soluble and particulate organics that often exceed biological oxygen demand levels of 10,000 mg/kg manure; therefore, the wastes from pig raising operations are considered to be high strength wastewaters. For this reason, aerobic treatment processes are usually avoided due to the large energy inputs that would be required for aeration or oxidant delivery. Anaerobic processes have a potentially important advantage of significantly reducing the 5-day biological oxygen demand (BOD_5) (to mitigate surface water impacts) while requiring low energy inputs. The conventional method of treatment of these streams has been the application of the anaerobic lagoon. Other methods with similar or improved potential include engineered anaerobic digestion processes.

Descriptions of research including the operating characteristics and performance of various anaerobic processes in the conversion of swine manure have been reviewed (Chynoweth et al., 1998). Most of the documented work relates to the testing of bench-scale or pilot-scale digester prototypes. The types of anaerobic treatment processes tested include: 1) Continuous Stirred Tank Reactors (CSTR); 2) Plug Flow Reactor (PF); 3) Attached Film Reactors (AF); 4) Baffle Flow Reactors; 5) Sequencing Batch Reactors (SBR); 6) Upflow Anaerobic Sludge Blanket (UASB); and, 7) Anaerobic Lagoons. A good summary of the performance of each of these types of processes on swine manure feedstocks has been reported in a review (Chynoweth et al., 1998).

Anaerobic digestion processes have been tested in the conversion of unseparated "whole" manures, with screened manures, swine operation flush water streams and wastewater fractions from settled manures, and/or lagoon supernatants. In determining the energy generation potential from swine waste, it is most important to consider the conversion efficiencies and rates for the whole manure material, which contains all of the organic waste fractions that potentially contribute to methane production. The digester designs that have received the most attention in obtaining careful measurements of conversion of unseparated "whole" manure to methane (including mass balances) have been the CSTR and the plug flow reactor.

The CSTR is comprised of a tank of the fermented mixture that is outfitted with a rigid, floating or flexible liner gas collection structure and that is continuously or frequently mixed. Mixing may be accomplished through mechanical stirring (which is usually employed in the laboratory) or through the recirculation of the liquid contents from one section of the digester to other sections, which is accomplished through the action of a recirculation pump. The CSTR prototypes are usually fed either continuously or semi-continuously at a high frequency within the retention time of the process. Commercial digesters that are designed on the basis of a single stage CSTR that combines the acid forming and methanogenic steps of the process can have a hydraulic retention time (HRT) of 10 to 60 days and fed at intervals of more than four times per day.

The Plug Flow digester, on the other hand, is usually constructed as an elongated, in-ground vessel that is outfitted with a flexible liner gas collection structure. The length to width ratio of the vessel is equal to or greater than 6:1. Commercial units can be constructed from earthen materials and liners as described in the literature (Jewell et al.,1980). In operation, the plug flow digester is simply fed at one end and effluent is withdrawn from the other. Since the digester is not mixed, the feedstock moves through the reactor as a "plug", often considered to be a traveling batch reactor. Most of the commercial plug flow digesters in use today are operated on dairy, beef and swine manures and are usually operated at an HRT of 10 to 30 days. The major constraint of this digester design is that the feedstock must be homogeneous and not prone to separation in the reactor vessel during digestion. This means that if the manure contains settleable material (e.g. grit), it must be settled out prior to feeding the plug flow digester. This also means that manure feedstocks must be of sufficient concentration and consistency as to avoid the formation of a float layer of buoyant solids, such as fiber.

The performance parameters that are frequently reported and that have the most impact on reactor economics are methane yield and methane production rate. The methane yield is the amount of methane (m^3) produced for every kg of feedstock hydrocarbon added to the reactor. This parameter is equal to the ultimate methane yield times the feedstock conversion efficiency. The methane production rate is expressed as the volume of methane produced per volume of reactor per day. A summary of methane production performance levels for five previous studies on the anaerobic conversion of whole (unseparated) swine manure is shown in Table 3.8.

Design Type	Scale	Temp °C	Influent Total Volatile Solids, %	Methane Production Rate, m^3/m^3-d	Methane Yield m^3/kg vs Added	Gas Quality, % CH_4	References
CSTR	Bench	35	5.04	2.6	0.26	64.2	Hashimoto, 1983
CSTR	Bench	35	5.04	3.1	0.31	61.1	Hashimoto, 1983
CSTR	Pilot	35	2.4	0.52	0.29	63	Stevens & Shulte, 1979
CSTR	Pilot	37	5.5	0.61	0.29	63.3	Petersen, 1982
Plug Flow	Bench	30	3.88	0.96	0.25	63	Floyd & Hawkes, 1986

Table 3.8 Summary of energy production performance or selected digester in the conversion of whole swine waste (unseparated)

The studies conducted to date on the conversion of whole swine manure consisted mostly of laboratory and pilot scale completely stirred tank reactors and a plug flow reactor trial. These previous bench and pilot reactors were fed with unseparated swine manure at a 2.4 to 5.5 percent total volatile solids (TVS) concentration; the CSTRs were operated at hydraulic retention times (HRT) of 5 to 20 days and a plug flow reactor was operated at a 10 day HRT. In general, methane yields for the CSTRs ranged from 0.26 to 0.31 m^3/kg VS added, while the plug flow reactor achieved a methane yield of 0.25 m^3/kg VS added. Methane production rates for the CSTRs ranged from 0.5 to 0.3 volumes per volume of reactor per day (v/v/d), while the one plug flow experiment achieved about 1 v/v/d. All of these reactors achieved reasonable swine manure conversion efficiencies in the range of 50 to 60 percent.

3.4 Development and Commercial Application of Anaerobic Digestion to Livestock Wastes

For more than 80 years, anaerobic digestion has been used in the U.S. for the treatment of concentrated organic sludges and waste streams generated by municipal wastewater plants and by industry. In general, digestion processes are applied to organic streams of 0.1 to 12 percent organic carbon. Since the 1930's, anaerobic digestion has been widely used in the U.S. for waste treatment. Currently, the process is implemented at the majority of the more than 16,000 Publicly Owned Treatment Works (POTWs) that are now in operation for sewage treatment and at thousands of industrial locations where concentrated organic streams are treated before final disposal. Most of the facilities in the U.S. use conventional designs that are expensive in construction and not optimized for energy recovery and utilization. Overall, the track record of anaerobic digestion as a sludge treatment process has been good, though sensitivities of the process to heavy metals and other toxic compounds that can be concentrated in municipal and industrial sludges have been documented (Metcalf and Eddy, 1992; Hayes and Theis, 1977).

This prior experience with sewage and industrial sludges has provided a good technology base and a high degree of confidence toward the application of anaerobic digestion for the conversion of livestock wastes to energy. The first digester designs applied to sewage sludge and nontoxic industrial organic waste consisted of unmixed stratified digesters with long retention times of 30 to 60 days, and later the limited mixed and/or recirculated digesters (resembling the CSTR) with retention times of 20 to 40 days. These designs were the mainstay of sludge stabilization process engineering for most of the Twentieth Century (Metcalf and Eddy, 1992).

The earliest attempt to widely apply sewage sludge digestion to the conversion of manures to energy took place in Europe in the wake of World War II. In Europe, it is still common to find operational digestion facilities designed for energy recovery and utilization. Since World War II, many digestion facilities were constructed on livestock farms in Europe (financed partly by the Marshall Plan) to recover the fuel value from organic wastes as a component of an austere energy economy. Today, most of the 600 farm-based anaerobic digestion facilities in Europe are very small with an output of less than 3,000 ft^3 of methane per day.

In the U.S. much of the early development of anaerobic digestion for livestock waste conversion was conducted in the 1970's and early 1980's. Much of the government support for this work was provided by USDA, NSF, ERDA, State Energy Programs, and the USDOE; the context for this support was to develop alternate supplies of gaseous energy and offer solutions for energy price relief for farms amid a national “Energy Crisis” and recession. For nearly a decade, this initial effort tested a number of conventional and second-generation designs on several types of manures, principally wastes from beef cattle, swine and dairy animals. Initially developed for dairy manure, some digester designs that were evaluated included completely mixed conventional systems, plug flow digesters, intermittently mixed units, anaerobic packed beds, and dry fermentation processes (Jewell, 1980).

Although these processes showed promise in achieving manure-to-biogas conversion efficiencies of 40 to 60 percent, improvements in biogas storage and utilization systems were largely not addressed in development before bioenergy funding levels were greatly reduced in the mid-1980’s due to the re-emergence of plentiful supplies of natural gas.

This period of development was followed by an era of commercial application of anaerobic digestion to beef, dairy, poultry and swine operations in the U.S., which was characterized by limited impact due to various factors. From 1980 to 1999, more than 120 anaerobic processes with gas collection covers were installed on U.S. livestock operations; of these, approximately half are still operating. Predominant types of anaerobic digesters that are operating on manure today include covered anaerobic lagoons, plug flow digesters (elongated tanks that are not mixed), and completely and intermittently-mixed digesters (Lusk, 1998).

The history of these initial commercial digesters, both operating and discontinued, reveals a number of lessons learned that point to development needs:

- Most of the digesters successfully operating today take advantage of benefits and product revenues that are not related to energy production. Some of the secondary benefits sought by farmers include odor control and fiber recovery.
- Digester performance relies on good operator attention and preventive maintenance. Livestock operations managers and workers, are not in the business of bioconversion and digester tasks are often neglected.
- Grit accumulation in digesters has caused a good number of failures, especially in digesters receiving poultry wastes and beef feedlot scrapings. Design of digesters needs to include pretreatment for sediment removal before manures are fed to digesters.
- A mismatch between biogas energy production and utilization can greatly hinder the economics of the digestion

system. Energy end-use packages that meet the site-specific needs for livestock operations are key to achieving maximum energy benefits from biogas produced from wastes.
- Up-front capital cost is often the greatest barrier to the installation of digestion systems (Lusk, 1998).

A new effort in technology development that addresses these issues and focuses on maximizing the potential benefits of anaerobic digestion would undoubtedly improve the reliability, the market drivers and the market penetration of Bioenergy Processing and Biorefining in the livestock industry.

3.5 Two-Phase Digestion

Two-phase anaerobic digestion is a process that derives its rationale from a fundamental understanding of the differences in nutritional, kinetic growth rates and environmental tolerances between the population of bacteria responsible for the fermentation of complex organic matter to volatile acids and the rather sensitive population of microorganisms responsible for the conversion of volatile acids to methane and carbon dioxide. Under conventional single-tank (i.e. combined-phase) digestion, both of these microbial populations coexist in the same vessel under conditions that represent a compromise of conditions for growth and feedstock conversion. For example, whereas the optimum pH for the acid forming phase is approximately pH 6, the single stage digester is usually operated at a pH of 7 to maintain stability of the more sensitive methane-forming population of microorganisms.

Two-phase anaerobic digestion sequentially separates the acid phase from the methane phase of fermentation so that each of these steps can be optimized for maximum performance. In its basic configuration, the process consists of a high-throughput, low-HRT, acid-forming (acidogenic), completely mixed reactor followed by a longer-HRT, methane-forming (methanogenic) anaerobic reactor. A diagram of the two-phase digestion process is shown in Figure 3.5.

The first stage reactor (digester) is a completely mixed anaerobic bioprocess that is operated at a hydraulic retention time of 1.5 to 3 days in order to wash out the slower growing methane forming microorganisms and to enrich the culture for the faster growing acidogenic bacteria. This reactor converts complex hydrocarbon compounds (contained in the influent feedstocks) to volatile acids with a concomitant production of carbon dioxide. The second phase reactor has a longer retention time of 5 to 10 days that promotes the stable operation of a methane-forming microbial culture; this reactor converts volatile acids to a biogas product that consists of methane and minor fraction of carbon dioxide. This particular phase can be performed by a wide range of digester designs that promote the growth and operation of methanogenic bacteria, including completely mixed, intermittently mixed, and plug flow reactor configurations.

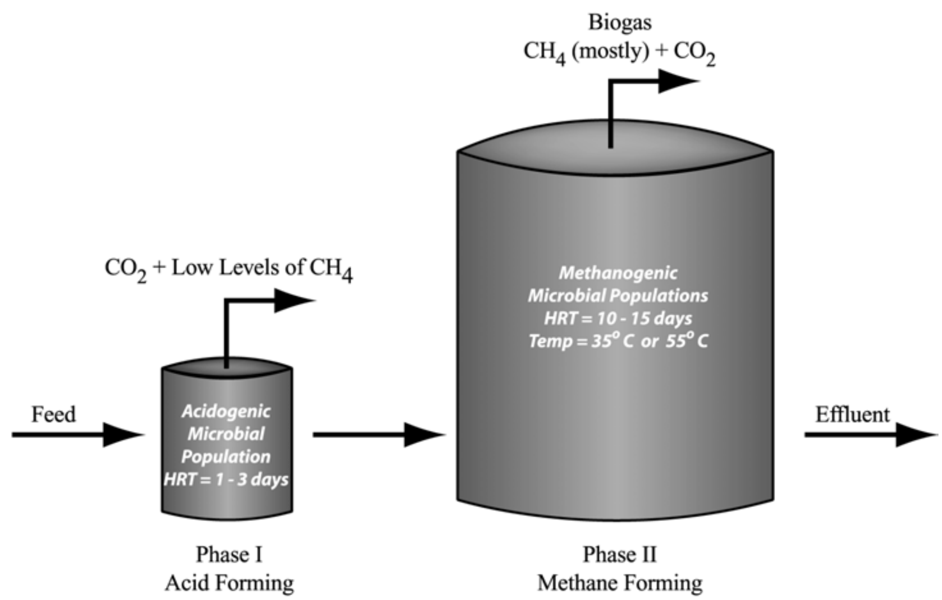

Figure 3.5 Two-phase anaerobic digestion

There are several important advantages that are intrinsic to the two-phase digestion process design. First, because each stage is optimized for maximizing the performance of the two distinctly different microbial communities, the digestion system is substantially more stable in performance than a conventional single-stage process that must be sub-optional for one or both populations of bacteria. The stability advantages of two-phase digestion over conventional (single stage) digestion has been documented in the literature for the conversion of sewage sludge to biogas (Ghosh et al., 1995; Ghosh, et al.,1985). In recent years, a full-scale conventional digester system at a sewage treatment plant in a suburb of Chicago that was suffering upsets due to overloading was successfully converted to a two-phase digestion system, commercially known as ACIMET®, that has operated without upset for more than 7 years (Srivastava, et al., 2000). This digester is shown in Figure 3.6.

Figure 3.6 Woodridge, Illinois ACIMET® Anaerobic Digester

Second, the overall rates that are achieved are substantially higher for both soluble and particulate feedstocks as indicated with industrial waste and sewage sludge (Ghosh et al., 1995). In the conversion of a number of manure feedstocks, this could make it possible to achie significantly greater efficiencies of conversion to energy with smaller processes (with lower HRTs). Third, two-phase digestion produces a biogas of significantly greater methane content and higher Btu value than is produced with conventional single-stage digestion processes. In general, conventional digestion produces a biogas with approximately 55 to 60 percent methane. Two-phase digestion, on the other hand, consistently produces a biogas containing over 70 percent methane. This is due to the action of the first phase of the process that removes much of the carbon dioxide generation potential of the feed when it pre-digests the complex organic compounds to volatile acids; thus a high CO_2 stream is formed from the first phase and a high CH_4 biogas stream is produced from the second phase. The biogas stream generated from the second phase can be maintained at a heating value above 700 Btu/ft^3, which is an advantage when integrating the process with high efficiency electricity generation equipment.

The purpose of the work described in this report was to determine the potential of two-phase digestion (HIMET^{SM}) to provide efficient conversion of swine manure to biogas energy, and to evaluate the potential of this process to achieve the reductions in pathogenic organisms that are need as a first step toward water management and the possible recovery of by-products. A conceptual schematic of how two-phase digestion could be implemented on a swine operation is shown in Figure 3.7.

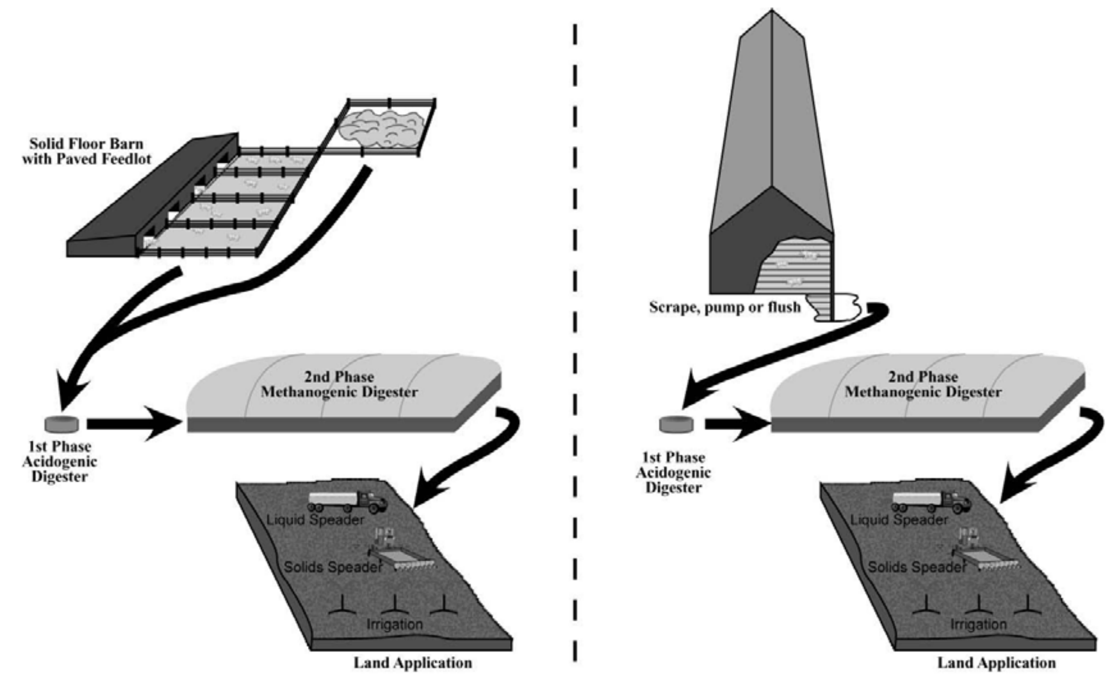

Figure 3.7 Conceptual schematic of swine operations utilizing two-phase digestion

4.0 Methods

Laboratory scale testing was conducted with swine waste to evaluate GTI's two-phase anaerobic digestion technology (commercially referred to as "HIMET^{SM}") to provide energy and environmental benefits for the cost effective management of waste residues generated from swine operations. Elements of this testing program included:

- The construction and testing of the two-phase anaerobic digestion units
  - One process train fed with swine manure
  - One process train fed with sewage sludge as a control
- The construction and testing of the single stage completely stirred tank reactors (CSTR)
  - One CSTR fed with swine manure
  - One CSTR fed with sewage sludge as a control
- Special studies to evaluate the potential of the swine digesters (CSTR and two-phase) to control pathogens

The following section describes the start-up, operation and analytical monitoring methods used to determine the performance of the anaerobic digestion systems.

4.1 Laboratory Digester Description

A total of six laboratory scale digesters were used in these studies. Two digesters, one fed concentrated activated sludge (CAS) and the other swine manure waste, were operated as a combined phase system. In addition, two digesters designed as two-phase systems consisting of an acid phase and methane phase digester were also operated on the two different feed stocks. Swine manure waste was fed to one of the two-phase system and its performance was compared to the performance of the two-phase system fed concentrated activated sludge.

Four of the digesters, two methane digesters and two combined phase digesters, utilized in this study were specially fabricated from "Plexiglas", a clear, hard, acrylic plastic. Total liquid volume of each of the digesters was 6 liters. A culture working volume of 3 liters was used for each methane phase digester and a culture working volume of 2 liters was used for the combined phase digesters. The digesters were mechanically mixed with a 3 inch marine-type axial impellor on a ½" stainless steel shaft, attached to a variable speed motor. The digesters were agitated at 200 rpm and maintained at 35°C. Ample ports were provided on the digester head plate (as well as the body of the digester) for probes, liquid addition, gas and liquid sampling. A schematic of the two-phase digester system consisting of one acid phase digester followed by one methane phase digester is shown in Figure 4.1. All of the combined phase and two-phase digesters were operated in a separate laboratory dedicated to the operation of the equipment as shown in Figure 4.2.

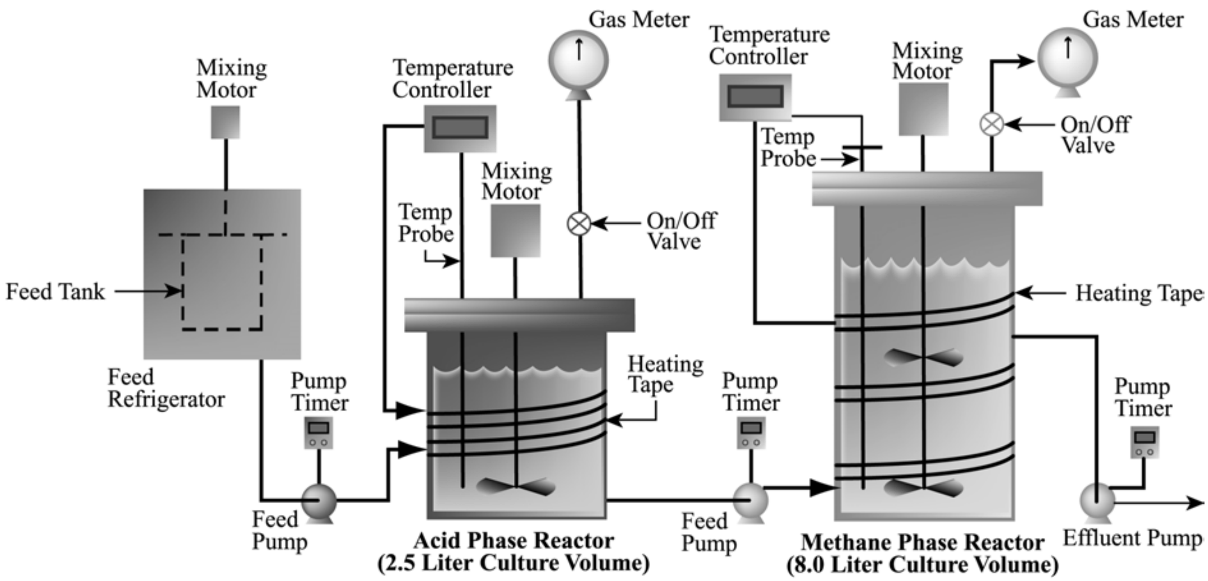

Figure 4.1 Two-Phase Reactor System

The acid phase reactors were each comprised of an Applikon 3 liter glass reactor vessel outfitted with a digital bio-controller (ADI 1030) and digital stirrer speed controller (ADI 1032). The reactor was mixed with 2 turbine blade impellors at 200 rpm and temperature was controlled at 35°C. The final working volume of the reactor was 1 liter. The combined phase digesters were operated at a hydraulic residence time (HRT) of 15 day and an organic loading rate of about 2.4 grams of volatile solids per liter of reactor per day for the manure fed and around 2.9 grams of volatile solids per liter of reactor per day for the sludge fed reactors.

Figure 4.2 Two-phase anaerobic digester units processing manure & sewage sludge feedstocks

The two-phase systems were operated at a total HRT of 15 days; each acid phase was operated at an HRT of 3 days and each methane phase was operated at an HRT of 12 days. The organic loadings were the same as the combined phase digesters. The HRT of the manure acid phase digester was lowered to 1.5 day near the end of test period in an effort to stimulate higher acid production (hydrolysis) from the organic fraction in the feed.

Initially, the two-phase systems were fed semi-continuously (i.e. once a day) by a draw and fill method. The sequence consisted of first removing a pre-determined volume from the first phase and replacing it with an equal amount a fresh feed. Next a pre-determined volume was removed from the methane phase and replaced with an equal volume of effluent from the acid phase. This mode of feeding was later replaced by a continuous feed operation with a series of timers and peristaltic pumps. Gas production was measured through a wet test meter.

Feeding for the combined phase digesters was achieved using a simple fill and draw technique. For each digester, a predetermined aliquot of the digester was withdrawn each day and replaced by an equal volume of feedstock. In this manner, the two combined phase digesters (sewage sludge and swine manure units) were fed in a semi-continuous mode through the duration of the testing.

4.2 Inoculum and Feed Source

As a source of microbial inoculum (seed) to start the lab scale digesters, effluents were collected from the acid stage and a methane stage of a commercially operated two-phase digester. The Greene Valley Municipal Waste Water Treatment plant, located in Woodridge, Illinois has been using the Two-Phase anaerobic digestion "Acimet" Process developed by the Gas Technology Institute (GTI) for municipal waste since 1995, see Figure 3.6. About two gallons of effluent from each stage of the digester was collected into a plastic container. The containers were filled almost to the brim, leaving a minimal headspace for gas to collect during the transport back to GTI.

At the same visit to the plant, concentrated waste activated sludge (WAS), which is feed to the ACIMET® acid stage digester, was also obtained. A total amount of about 40 gallons was collected and transported back to GTI where it was processed for laboratory use. The feed containers were then placed into a freezer for storage and removed as needed.

In addition to the concentrated activated sludge feed, it was also necessary to obtain swine manure. The waste was obtained from the Kellogg Farm, located about 50 miles from GTI in Yorkvillle, Illinois. The waste manure was pumped from a lagoon into six, five-gallon carboys and transported back to GTI were it was processed for laboratory use. Upon arrival at GTI, the carboys were mixed and the contents were screened to remove debris etc. before distribution into five-gallon containers. The feed containers were then placed into a freezer and removed as required. All feedstocks were analyzed for physical and chemical characteristics. The tests conducted are described later in this section.

4.3 Initial Startup

Initially, all the laboratory digesters were inoculated with effluent from the municipal sewage treatment plant located in Woodridge, Illinois. After each digester was charged with the digested sludge, the digesters were purged with an inert gas to provide an anoxic atmosphere with-in the reactor. Next, the digesters were attached to the gas measuring meters and the heating and mixing devices were activated. The systems were not fed for a day or two after which time they were fed concentrated activated sludge on a daily bases. Following approximately two to three retention times of stable performance on sewage sludge, one set of each type of digester was gradually changed over to the manure feedstock. All digesters were operated for approximately two hydraulic retention times, about 30 days, before the steady state period was reached. Then the steady state operation was extended for another 30 days during which time performance data was collected.

4.4 Analytical Methods

For each of the digesters operated in this project, a number of operational parameters were monitored to determine the effectiveness of each type of digester in the conversion of the organic feedstocks. Digester gas production was measured using a gas wet test meter (American Meter Wet Test) and gas composition was determined by gas chromatography (Carle 400-AGC Gas Chromatograph with thermal conductivity detector).

Influent and effluent samples from the laboratory digesters were analyzed for pH, temperature, volatile fatty acids, total solids, volatile solids and alkalinity. Initially, each batch of feedstock was analyzed for pH, total solids, volatile solids, volatile fatty acids. These analyses were conducted using the techniques described in Standard Methods (APHA, 1998).

4.5 Digester Performance Characterization

In general, digester characterization procedures were aimed at obtaining mass balance and biogas generation information from each of the digesters. Table 4.1 presents the analysis schedule for the laboratory digesters, indicating which parameters were measured on a daily, weekly and steady state basis. As shown in this table, biogas volume measurements, temperatures and pH were among the parameters most frequently collected as data; these measurements were collected during startup, in the initial non-steady state period and during steady state.

Analysis Parameters	*Each Batch of Feedstock*	*Effluents of Bioprocesses*		
		Daily	*Weekly*	*Steady State*
Total solids	X		X	X
Volatile solids	X		X	X
PH	X	X		X
Total volatile acids	X		X	X
Temperature of digester		X		X
Ambient temperature		X		X
Gas production		X		X
Gas composition			X	X

Table 4.1 Analysis Schedule for the Laboratory Scale Digesters

4.6 Pathogen Control Measurements

Microorganisms that can cause illness or disease in humans or other animals are of a concern in manures of all types and this includes swine or hog manures. Examples of some potential manure-borne microorganisms and the corresponding diseases of concern are shown in Table 4.2.

Microorganism	*Disease*
Campylobacter	Bloody diarrhea
Escherichia coli	Gastrointestinal disease
Leptospira spp.	Kidney infection
Yersinia enterocolitica	Gastrointestinal infection
Cryptosporidium parvum	Cryptosporidiasis
Giardia lamblia	Giardiasis
Toxoplasma spp.	Toxoplasmosis

Table 4.2 Examples of manure borne organisms and their corresponding diseases

Evaluation of the potential survival of disease organisms in certain environments or processes is often conducted using special tests for indicator organisms. For example, in the evaluation of the ability of anaerobic digestion processes to achieve reductions in pathogenic microorganisms, it is often useful as well as safer to conduct experiments where the sought-for organism is an indicator rather than a virulent disease agent. Therefore, the GTI evaluations of the pathogen reduction potential of digestion processes were carried out using indicator microorganisms that are often referred to in the literature and in guidelines and regulations regarding manure disposal practices. Indicator microorganisms used in this study included:

- Total Coliform Bacteria
- Fecal Coliform Bacteria
- Fecal Streptococcus Bacteria

In order to determine the control of these microbially derived infections by the two-stage anaerobic digestion process using swine manure as the feedstock, and its ability to meet or exceed the classification for a Class A sludge under 40 CFR Part 503 C, the following protocols were used for the measurements of indicator organisms.

4.6.1 Standard Total Coliforms

The test for total coliforms in sewage sludge was executed according to the Standard Method for Water and Wastewater (APHA 1998. 9221 B. Standard Total Coliform Fermentation Technique, pg. 9-48). The presumptive phase of the testing was carried out. A summary of this method is as described in this section.

Fresh samples of the sludge from the acid phase and the methanogenic phase reactors were collect and transferred immediately to the anaerobic glove box (Coy Laboratory Products, Ann Arbor, MI) where it was transferred into tubes containing a growth medium; the composition of this medium is described in Table 4.3.

The fermentation tubes were arranged in rows of 10 tubes in a test tube rack and the sludge slurry was diluted serially in ten fold steps. Replicate samples were prepared and placed into the medium. The samples were incubated at 35 ±0.5C. The tubes were monitored daily for 72 hours. The numbers of tubes and their corresponding dilutions were visually noted and results were reported as “most probable numbers” as instructed by Standard Methods (APHA, 1998).

Constituent	Amount	Unit
Tryptose	20.0	grams
Latose	5.0	grams
K_2HPO_4	2.75	grams
KH_2PO_4	2.75	grams
NaCl	5.0	grams
Sodium Lauryl Sulfate	0.1	grams
Reagent-Grade Water pH = 6.8 ± 0.2	1.0	liter

Table 4.3 Medium for standard total coliform fermentation technique, i.e. 9221 B

4.6.2 Fecal Coliform Procedure

The test for fecal coliforms in the pig manure treatment sludge was executed according to the Standard Methods for Water and Wastewater (9221 E. Fecal Coliform Procedure, pg. 9-54). By elevating the temperature of incubation, the determination of fecal coliforms was conducted as a subset of the total coliforms detected in the previous test.

Fresh samples of the sludge from the acid phase and the methanogenic phase reactors were collect and transferred immediately to the anaerobic glove box (Coy Laboratory Products, Ann Arbor, MI) where it was transferred into tubes of the medium described in Table 4.4.

Constituent	Amount	Unit
Tryptose	20.0	grams
Latose	5.0	grams
Bile salts mixture	1.5	grams
K_2HPO_4	4.0	grams
KH_2PO_4	1.5	grams
NaCl	5.0	grams
Reagent-Grade Water pH = 6.9 ± 0.2	1.0	liter

Table 4.4 Medium for fecal coliform procedure, i.e. 9221 E

The fermentation tubes were arranged in rows of 10 tubes in a test tube rack and the sludge slurry was diluted serially in ten fold steps. Replicate samples were prepared and placed into the medium. The samples were incubated in a waterbath with the temperature set at 44.5 ±0.5C. The tubes were monitored daily for 72 hours and results were reported as "most probable numbers" as instructed by Standard Methods (APHA, 1998).

4.6.3 Fecal Streptococcus Group

Fecal streptococci have been applied with the fecal coliform groups to differentiate human fecal contamination from that of other warm-blooded animals, such as swine. These indicator microorganisms are more common in these other animals, so the ratio of fecal coliform to fecal streptococcus is 0.7 or less. The Multiple-Tube Technique (9230 B. Standard Methods for the Examination of Water and Wastewater, 20th Edition, pg. 9-75) was applied to determine the presence and absence of fecal streptococcus bacteria and to obtain an estimation of their numbers in the two-phase digestion system with the methanogenic phase incubated at 55 ± 0.5 C. The culture media used in this phase of the study is described in Table 4.5.

Constituent	Amount	Unit
Beef extract	4.5	grams
Tryptone	15	grams
Glucose	7.5	grams
NaCl	7.5	grams
Sodium Azide, NaN_3	0.2	grams
Reagent-Grade Water	1.0	liter

Table 4.5 Azide dextrose broth for multiple-tube technique for fecal streptococcus, i.e. 9230 B

A series of tubes of the Azide Dextrose broth were set up with a serial dilution of the swine sludge from the feedstock, first phase bioreactor effluent, and the second phase bioreactor effluent. The tubes were incubated at 35 ± 0.5°C and examined for the presence of turbidity every 24 hours for a total of 72 hours. Any tubes showing turbidity was transferred to the Enterococcus agar described in Table 4.6 for the confirmation test.

Constituent	Amount	Unit
Peptones	20.0	grams
Yeast Extract	5.0	grams
Bile	10.0	grams
NaCl	5.0	grams
Sodium Citrate	1.0	grams
Esculin	1.0	grams
Ferric Ammonium Citrate	0.5	grams
Sodium Azide, NaN_3	0.2	grams
Agar	15.0	grams
Reagent-Grade Water	1.0	liter

Table 4.6 Enterococcus agar for presumptive test procedure, i.e. 9230 B

Results were principally developed from the testing of two digester designs operated on swine manure and digester sludge (the feedstock control) under two hydraulic retention time conditions at a temperature of 35ºC. Results collected from this research included the characterization of the manure and sewage sludge feedstocks, measurements of key performance parameters on each of the digesters, and reductions of pathogen indicators observed to occur as the feedstock passed through the digesters.

5.0 Results

5.1 Characterization of Swine Manure and Sewage Sludge Feedstocks

All of the swine manure used in digester testing was collected from the under floor manure collection pit situated below a hog feeding barn of a local swine raising operation; the waste activated sludge material was obtained from the Woodridge Sewage Treatment Plant. The results from the analysis of manure and sludge feedstocks are presented in Table 5.1. The values reported in this table represent averages of assays on more than six batches of manure and six batches of sewage sludge. As shown in the table, the swine manure had a consistency in the average range for swine manure described in the literature (see section 3.07), approximating 4 percent total solids and nearly 3 percent volatile solids. The sewage sludge contained a comparable consistency of about 5.5 percent total solids and a little more than 4 percent volatile solids ---- well within the normal range for waste activated sludge (i.e. sewage sludge).

Parameter	*Sludge*	*Manure*
TS, g/l	55.0	41.0
VS, g/l	42.4	27.7
VS, % of TS	77.1	67.6
PH	6.3	7.2
Volatile Acids		
Acetic	1279	5918
Propionic	404	1586
Isobutyric	117	282
Butyric	313	1092
Isovaleric	130	270
Valeric	356	131
Isocaproic	57	9
Caproic	2	60
Total	***2528***	***9348***

Table 5.1 Analysis of feedstocks used for theoperation of laboratory digesters

The largest differences between the manure and sewage sludge feedstocks can be seen in the concentrations of volatile acids present in the materials. The sewage sludge contained approximately 2,300 mg/l total volatile acids while the manure material contained over four times that concentration in total acids. This may reflect a significant conversion activity that is taking place through the action of acid forming bacteria within the manure storage pit at the hog operation that causes more than a quarter of the organic content of the manure to be converted to volatile acids that can accumulate to levels approximating 1 percent.

It is interesting to note that the swine manure material which contained the higher titer of volatile acids had a pH level significantly higher than the sewage sludge. This is due to the substantially higher buffering capacity of the swine manure that maintains pH values at circum-neutral levels even when volatile acids accumulate to elevated levels.

5.2 Digester Performance

Initially, all laboratory digesters were started using cultures obtained from the municipal sewage treatment plant of Woodridge, IL; this facility was ideal for collecting cultures since it has successfully operated a full-scale two-phase digester system (which was designed after the ACIMET® Process developed and patented by the Gas Technology Institute) for the stabilization sewage sludge. During start-up, all digesters (two combined phase digesters and two two-phase digesters) were started on raw sewage sludge (biosolids) feedstock obtained from the Woodridge treatment facility. During this initial startup period, manure feedstock was collected from a hog raising facility near Yorkville, IL. The manure was characterized and stored for future use in the digestion experiments.

Following approximately two retention times of stable operation on sewage sludge, one set of each type of digesters was gradually changed over to the manure feedstock. Both combined phase digesters were operated at a hydraulic retention time (HRT) of 15 days. Both two-phase digesters were operated at a total HRT of 15 days; the acidogenic phase of each of the two-phase digestion systems was operated at an HRTof 3 days and the methanogenic phase of each of these systems was operated at an HRT of 12 days. All digester systems were fed once a day using a fill and draw feeding technique. The organic feed loading rates for the manure digester units were maintained at around 2.3 grams of volatile solids per liter reactor per day and the loading rates for the sewage sludge units were maintained at around 2.9 grams of VS per liter reactor per day.

The starting point for the manure digesters was considered to occur when the units had acclimated to 100 percent manure feedstock. Beyond this point, all digesters were operated for approximately two hydraulic retention times (approximately 30 days) before a steady state period was reached. Data from the steady state period (extending for another two hydraulic retention times or 30 days) was then collected; parameters measured included biogas production, methane content of biogas, total solids content of feed and effluent, total volatile solids content of feed and effluent, and volatile acids content of reactor mixed liquor and feedstock. Daily methane production data from the reactors are graphically shown in Figures 5.1 to 5.4.

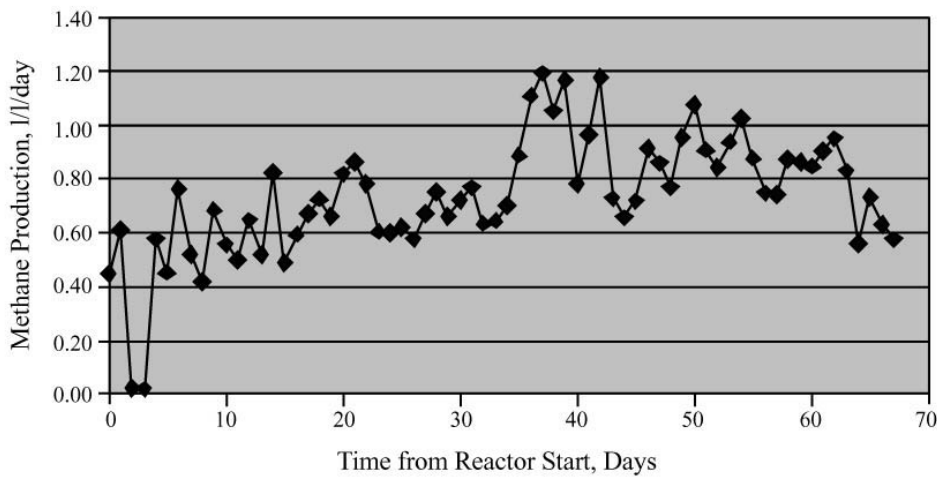

Figure 5.1 Methane production for the two-phase manure digester

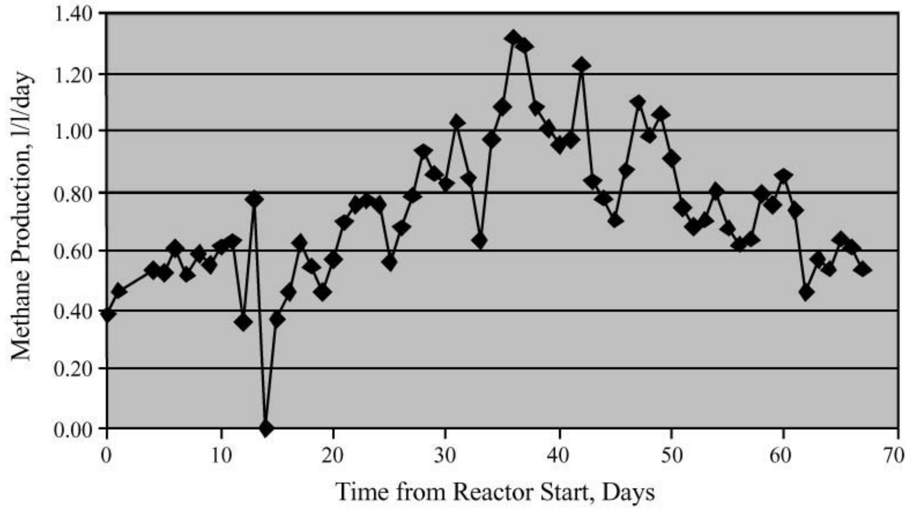

Figure 5.2 Methane production for the combined phase manure digester

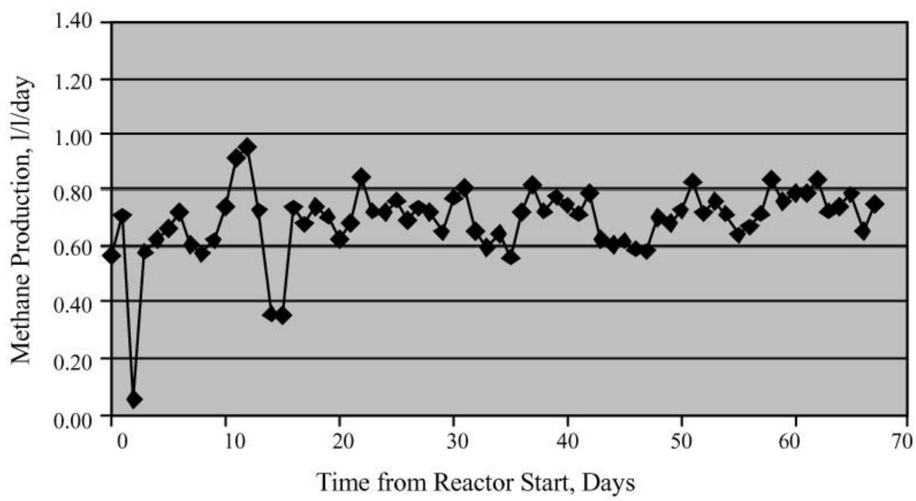

Figure 5.3 Methane production for the two-phase sewage sludge digester

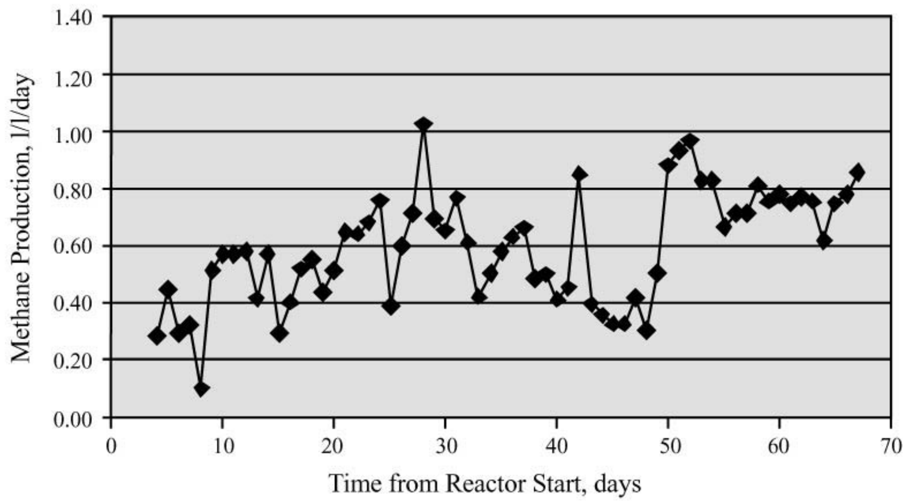

Figure 5.4 Methane production for the combined phase sewage sludge digester

The methane production profiles shown in Figures 5.1 and 5.2 indicate that the GTI methodology of digester startup is highly effective with swine manure feedstocks; within five to ten days following startup, methane output was comparable to the output at steady state. Performance data collected from the digester units during steady state operation are summarized in Table 5.2. The data summary of Table 5.2 represents averages of performance data taken over the steady state period of operation which occurred between Day 35 and Day 65 following startup of each digester.

Parameter	***Swine Manure***		***Sewage Sludge***	
	Combined Phase	***Two Phase***	***Combined Phase***	***Two Phase***
Total hydraulic retention time, days*	15	15	15	15
Organic loading rate, g/liter/day	2.5	2.28	2.9	2.9
Methane production, liter/liter reactor/d	1.18	0.82	0.64	0.74
Methane composition, % (menthanogenic stage)	65	65	64	65
Methane yield liter/g VS** added	0.47	0.36	0.24	0.28

** Acid Phase Distesers HRT = 3 days*
*** VS = Volatile Solids (ash-free organic feed)*

Table 5.2 Summary of data on anaerobic digestion performance at an HRT of 15 days

In the conversion of sewage sludge and manure, two-phase digestion exhibited significantly higher levels of methane yield performance and stability than was observed with the combined phase digesters as evident in comparing the daily methane production profiles of Figures 5.1 through 5.4 and as represented in the bar chart of Figure 5.5. In the conversion of sewage sludge, methane production was 11 percent higher in the two-phase digestion unit than in the combined phase digester; methane yields with two-phase digestion reached 0.25 liters per gram of volatile solids added (l/g VS_A) versus 0.22 l/g VS_A observed for the combined phase unit.

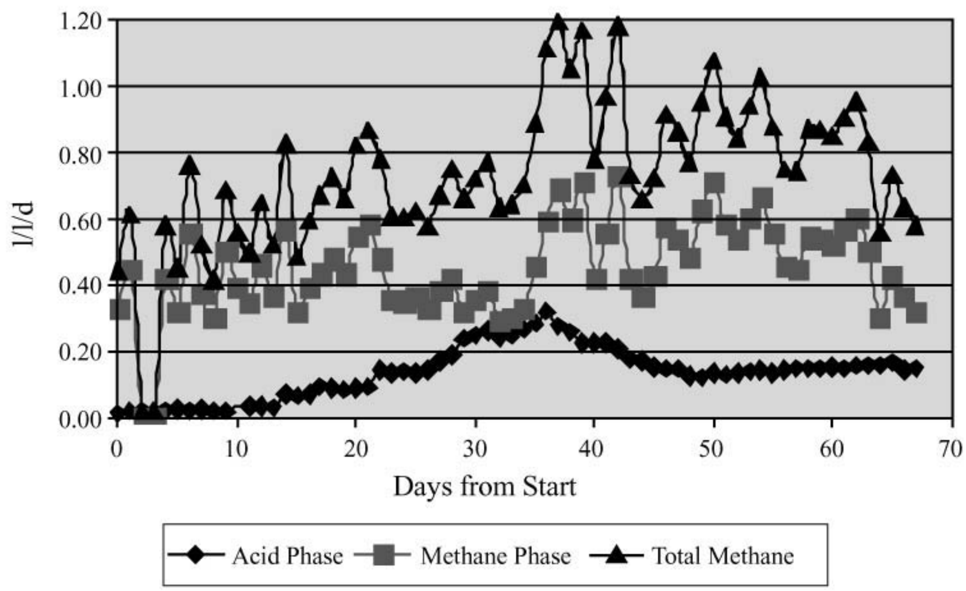

Figure 5.5 Methane production from both stages of the two-phase manure digester

In general, good performance was been achieved from the two-phase and the combined phase digesters operating on swine manure feedstock. However, the two-phase digestion unit exhibited a methane yield that was 15 percent higher than the yield observed with the combined phase unit (i.e. 0.39 l/g VS_A achieved with the two phase unit versus 0.34 l/g VS_A for the combined phase unit) as shown in Figure 5.5. This methane yield represents 80 percent of the theoretical maximum achievable methane output and is equivalent to generating over 6.2 ft^3 of methane per pound of volatile solids added (ft^3/lb VS_A). In other words, the two-phase digestion system converted 80% of the organic feedstock to methane compared to a conversion efficiency averaging about 68% with the combined phase digester. The combined phase (single stage) digester achieved an average methane yield of about 5.4 $ft^3/lb\ VS_A$ in the conversion of manure.

The manure digesters out-performed the sewage sludge controls in terms of biogas output, percent methane content of the biogas and methane yield. The manure digesters averaged about 50 percent more methane yield than the corresponding digesters operating on sewage sludge. Methane yields ranged from 0.22 to 0.25 $l/g\ VS_A$ in the sewage sludge digesters compared to over 0.34 $l/g\ VS_A$ generated from the manure digesters.

The two-phase digesters also exhibited good methane content in the biogas generated from the methane phase, whether operated on sewage sludge or manure. Methane content of biogas generated from the two-phase digestion of sewage sludge was approximately 70 percent, versus a methane content of 64 percent achieved with the conventional combined phase unit (CSTR). In the digestion of manure, the two-phase digester also achieved elevated Btu biogas with a methane content that averaged 72 percent. Interestingly, the combined phase manure digester also achieved a methane content of 72 percent in the biogas.

The ability of the combined phase unit to produce such a high level of methane in the biogas is likely due to the high degree of predigestion that occurred in the under-floor swine manure storage tank prior to GTI collecting the sample. This predigestion achieved a partial conversion or hydrolysis of the manure to volatile acids as evidenced by the concentrations of volatile acids in the manure feedstock that ranged between 6 and 9 percent (see Table 5.1). During the partial conversion of manure to volatile acids, a significant amount of carbon dioxide is formed and lost from the open storage tank; this CO_2 would normally be released to the biogas of the anaerobic digestion process if the manure were not predigested. This phenomenon is probably site specific and cannot be expected to occur with a high degree of dependability at many hog raising operations. Under circumstances where swine manure storage does not achieve a high degree of predigestion, the combined phase digester would not have been able to produce a biogas enriched in methane while the two-phase digestion unit (with an engineered initial phase that promotes predigestion or partial hydrolysis of the manure) would still have been able to produce elevated methane content biogas (>70 percent) from the methanogenic phase.

In the two-phase digestion process, more than 80 percent of the methane that was produced was generated by the methanogenic stage as seen in Figure 5.6. The methane concentrations of the biogas streams generated by each digestion unit process tested in this project are shown in Table 5.3. Also shown in this table are the volatile acid concentrations and pH values that can help explain the differences of gas quality between the unit processes. In general, the highest levels of methane in the biogas were observed in the methane stage of each of the two-phase digesters where volatile acids were reduced to the lowest levels and where the pH values were maximized to the vicinity of pH 8. The equilibrium equation for the dissolution of carbon dioxide in water is as follows:

$$CO_2 \overset{K_H}{\rightleftarrows} H_2CO_3 \overset{K_1}{\rightleftarrows} HCO_3^{-} \overset{K_2}{\rightleftarrows} CO_3^{-2}$$

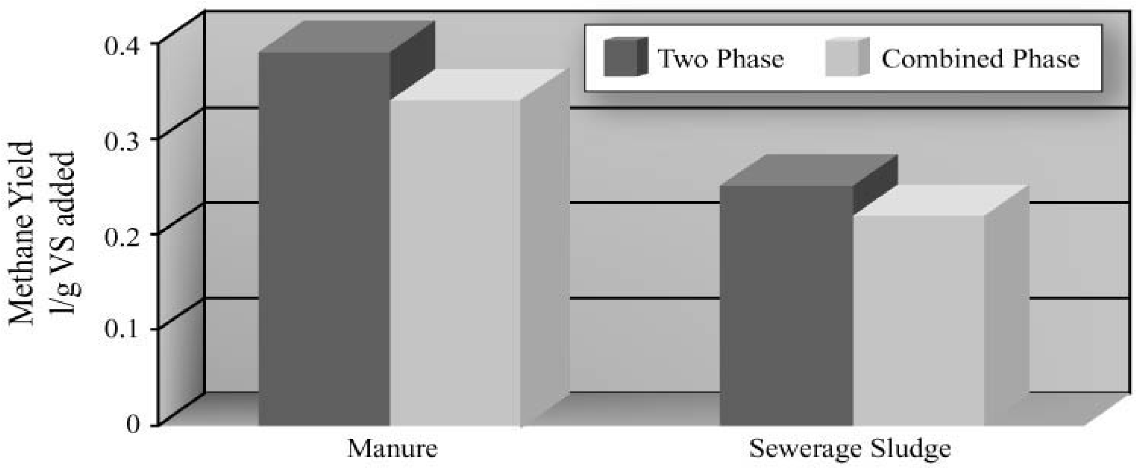

Figure 5.6 Comparison of methane yields achieved with Combined Phase and Two-Phase Anaerobic Digestion

As the volatile acids are consumed and pH is increased, the above equilibrium equation for dissolution of CO_2 is shifted to the right (Stuum and Morgan, 1981). As the equilibrium is shifted to the right, more carbon dioxide is dissolved into the water phase of the digester contents. Unlike carbon dioxide, on the other hand, methane is highly insoluble in water and changing the pH does not enhance its solubility. Therefore, digesters that operate at a higher pH are likely to experience increased CO_2 dissolution in the water fraction and decreased CO_2 being released to the biogas stream of the digester. This results in an enrichment of methane in the biogas. The data in Table 5.3 that show a high concentration of methane to levels above 70 percent for digesters corresponds to elevated effluent pH values approaching pH 8. This relationship is consistent with the aqueous equilibrium relationships for CO_2 solubilization in water.

Operating Conditions & Performance Parameters	Manure Two Phase		Sewage Sludge		Manure Combined Phase	Sewage Sludge Combined Phase
	Acid Phase	Methane Phase	Acid Phase	Methane Phase		
Hydraulic Retention Time, Days	3	12	3	12	15	15
PH	7.4 - 7.6	7.8 - 8.0	7.1 - 7.3	7.5 - 7.8	7.9 - 8.0	7.3 - 7.6
Volatile Acids, mg/l						
Acetic	4879	1072	577	282	2053	1373
Propionic	2462	700	1527	212	873	189
Isobutyric	536	37	201	15	68	16
Butric	1123	33	75	56	61	20
Isovalaric	735	63	439	44	190	80
Valeric	188	14	73	3	16	2
Isocaproic	41	3	214	1	4	15
Caproic	64	6	83	2	4	1
Total VA, as Acetic, mg/l	8596	1732	2426	551	2971	1594
Methane Content in Biogas, % Methane	64	72	69	72	70	64

Table 5.3 Volatile acid concentrations and biogas quality observed in the anaerobic digestion unit process: steady state averages.

5.3 Pathogen Reduction

An important prerequisite for by-product recovery from manures is the effective, low-cost control of manure-borne disease organisms. This research was designed to determine the potential of using anaerobic digestion for reducing pathogenic microorganisms in swine manure to the extent of achieving the status of a Class A biosolids as defined by 40 CFR Part 503C (USEPA, 1993).

The general protocol used in this work was to take influent and effluent samples of swine manure from two types of anaerobic digesters and examine the concentrations of pathogen indicators to determine the potential for reductions of harmful microorganisms. Analysis of pathogen indicators in human waste (sewage sludge) was used as a positive control. The types of manure digesters that were used in the testing included a two-phase anaerobic digester that was operated at 35°C (15 days HRT) and a thermophilic, two-phase digester (operated at approximately the same HRT as the two-phase system) where the acetogenic phase was operated at 35°C and the methogenic phase was operated at 55°C. The mesophilic two-phase digester was operated as previously described in Section 4.0 of this report. The thermophilic two-phase digester was also fed with swine manure feedstock and feeding was accomplished in a fill and draw mode.

After both digester trains were brought to steady state in operation, samples were taken from the influent and effluent of each unit operation, including the effluent of the acid phase of the two-phase digester.

Analysis of pathogens and pathogen indicators in the manure feedstocks and in digester effluents indicate that the digestion process has the capability to achieve good reductions of total coliforms, salmonella, and fecal streptococcus exceeding 90 percent. Data on the concentrations of total coliforms, fecal coliforms and fecal streptococcus in the samples that were analyzed are presented in Tables 5.4, 5.5, and 5.6. Both digester systems were able to achieve more than 95% reductions in pathogen indicators. The reductions for fecal coliforms in the digesters are graphically shown in Figure 5.7.

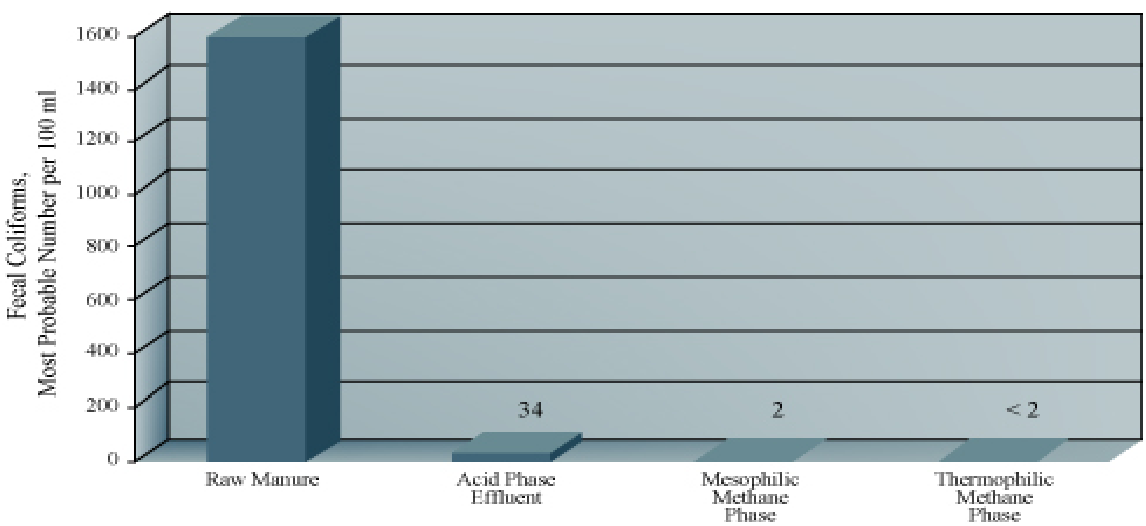

Figure 5.7 Reductions in Fecal Coliforms Achieved with Two-Phase Anaerobic Digestion

The potential ability of both digesters to control pathogenic organisms in swine manure appears to be substantial. In particular, the two-phase digestion system operated at 35°C was able to reduce total coliforms from 170 organisms per 100 ml to 8 per 100 ml (a 95% decrease), while fecal coliforms were reduced from 1,600 per 100 ml down to 2 per 100 ml and fecal streptococcus was reduced from over 1,600 per 100 ml down to 22 per 100 ml. On the other hand, the thermophilic unit was able to reduce all of the indicator organisms down to non-detect (less than 2 per 100 ml).

The data indicate that thermophilic digestion at 55°C has the ability to achieve reductions of pathogens that would comply with the standards for Class A biosolids; this would allow considerable latitude for by-product recovery from swine manure. The two-phase digestion process is also effective in achieving pathogen reductions that are nearly equal to reductions achieved with thermophilic digestion. The data suggest that a combination of the two processes (e.g. a mesophilic acidogenic stage followed by a thermophilic stage) would also be an effective treatment for producing a Class A biosolids material.

Waste Source	*Number of Coliforms in 100 mL*	*Comments*
Human waste	280	Positive control
Swine feedstock	170	Untreated from swine lagoon
Swine effluent from first phase digester, 35°C	22	
Swine effluent from second phase (Methanogenic phase) digester, 35°C	8	
Swine effluent from second phase (Methanogenic phase) digester, 55°C	Below detection limits	Minimum detection limits with this assay is 2 or less coliform per 100 mL

Table 5.4 Total coliforms in the swine wastes treated with two phase anaerobic digestion

Waste Source	*Number of Coliforms in 100 mL*	*Comments*
Human waste	12	Positive control
Swine feedstock	1600	Untreated from swine lagoon
Swine effluent from first phase digester, 35°C	34	
Swine effluent from second phase (Methanogenic phase) digester, 35°C	2	
Swine effluent from second phase (Methanogenic phase) digester, 55°C	Below detection limits	Minimum detection limits with this assay is 2 or less coliform per 100 mL

Table 5.5: Fecal coliforms detected in swine wastes treated with two phase anaerobic digestion.

Waste Source	*Number of Fecal Streptococcus in 100 mL*	*Comments*
Human waste	2	Positive control
Swine feedstock	≥1600	Untreated from swine lagoon
Swine effluent from first phase digester, 35°C	170	
Swine effluent from second phase (Methanogenic phase) digester, 35°C	22	
Swine effluent from second phase (Methanogenic phase) digester, 55°C	Below detection limits	Minimum detection limits with this assay is 2 or less coliform per 100 mL

Table 5.6: Fecal Streptococcus Detected in Swine Wastes Treated with Two Phase Anaerobic Digestion

6.0 Discussion

Significantly, the laboratory experiments performed in this effort have indicated that two-phase digestion has potential performance capabilities that may offer substantial future improvements in efforts to achieve greater efficiencies the recovery of energy as well as greater design flexibility for the future recovery of by-products from swine manures while addressing key concerns over impacts to the environment and to the public health. The sections to follow discuss some of the possible advances that can be realized from the continued development and scale-up of two-phase digestion for commercial deployment in the swine industry. For purposes of discussion, GTI's two-phase digestion approach to the management of swine manure will be referred to as "HIMET^{SM}"; HIMET^{SM} is the animal waste application of GTI's Proprietary ACIMET® technology.

6.1 HIMET^{SM} Two-Phase Digestion Comparison to Conventional Digestion

The results from this comparative laboratory study comparing two-phase digestion with completely mixed combined phase digestion indicate that the GTI HIMET^{SM} technology has significant performance advantages over conventional digestion technology. Conventional digestion of manure is usually commercially deployed as a combined phase digester using either the plug-flow or the mixed digester design. The plug flow design, in particular, has been the most frequently used digester for applications to swine and dairy manures over the past twenty years. In the conversion of swine manure to biogas energy, the performance data from the laboratory show that the HIMET^{SM} technology can provide the following potential performance advantages over conventional digestion:

- A 10-15 percent increase in methane output per unit weight of swine manure with methane yields of up to 6.2 ft^3/lb of volatile solids
- An improved quality of biogas product with an increase of heating value to above 720 Btu/ft^3 of biogas
- Less variation in daily methane production
- Greater control of volatile acids in the presence of sensitive methanogenic populations which leads to greater digester stability

The comparison of digester stability parameter values in Table 6.1 indicate that the two-phase HIMET^{SM} digestion process exhibited a more stable performance than the conventional combined phase system in terms of variation in gas production and in terms of average volatile acids that were permitted to accumulate in the methane forming reactors. It can be seen in Table 6.1 that the daily methane production data for the HIMET^{SM} two-phase digester had a lower variation in terms of standard deviation and average deviation than the conventional combined phase digesters for manure and sewage sludge feedstocks. A reduced variation in daily biogas production would indicate that the two-phase HIMET^{SM} units experienced less stress than the conventional combined phase units. For example, the average deviation as a percent of the mean for daily methane production from the combined phase digesters at steady state was 22% and 26% for manure and sewage sludge conversion, respectively, compared to 14.6% and 7.5% for the two-phase digesters that processed manure and sewage sludge.

STABILITY PARAMETER	MANURE		SEWAGE SLUDGE	
	2-Phase	Combined Phase	2-Phase	Combined Phase
Standard Deviation, % of Mean	19.0	26.9	9.7	30.1
Average Deviation, % of Mean	14.6	22.1	7.5	25.8
Average Total Volatile Acids in Effluent at Steady State mg/l as Acetic*	1732	2971	551	1594

Table 6.1 Comparison of Digester Stability Indicators at Steady State

*As measured in the effluents of the methanogenic phase of the two-phase digesters and in the effluents of the combined phase digesters

It is note-worthy that the conventional digester units not only experienced larger variations in daily methane production but also exhibited substantially higher accumulations of volatile acids that may have produced stress on methanogenic populations. It is claimed in the literature that among the common signs of digester distress is the accumulation of volatile acids (Metcalf and Eddy, 1972, Ghosh, et al., 1975). In the digestion of manure, the bench-scale two-phase unit exhibited about half the concentration of volatile acids (about 1,700 mg/l) in the methane phase as measured in the combined phase unit on the same feed (about 3,000 mg/l). The same general comparison for the digester designs holds true for sewage sludge digestion. The data show that two-phase digestion is measureably more stable than the combined phase reactor (whether operating on sewage sludge or swine manure) when considering the variations of methane output and volatile acid concentrations as key indicators of digester stress.

Overall, the methane production performances observed with the GTI laboratory swine manure digesters (both combined phase and two phase) compare favorably with the methane yields reported in the literature for the digestion of swine manure (whole, scraped or screened) which range from 0.20 to 0.35 l/g VS added (3.2 to 5.6 ft^3/lb VS added) (Roustan, et al., 1984; Aubart and Bully, 1984; Ferrero, et al., 1984; Chynoweth, et al., 1998; Hill and Bolte, 2000). Generally, methane yields from the GTI manure digesters were in the range of 0.30 to 0.39 l/g VS added (4.8 to 6.2 ft^3/lb VS added) about 15 to 25 percent higher than most literature values reported for swine manure conversion. As previously presented, the two-phase swine manure digesters exhibited a methane yield of 0.39 l/g VS added (6.2 ft^3/lb VS added) and a methane production rate of approximately 0.9 volumes per volume reactor per day. This performance represents a swine-manure-to-energy conversion efficiency of 80-85% (assuming an ultimate methane yield of 0.47-0.5 l/g VS added) that is achievable with two-phase HIMET^{SM} anaerobic digestion.

Conversion performance with commercial deployment of the technology would depend on site-specific factors, however, it is expected that similar levels of performance could be achieved at a pilot and commercial scale based on GTI's experience in the scaleup of two-phase digestion for full scale application to sewage sludge treatment (Ghosh, et al., 1995; Srivastava, 1996). In view of the projected advantages, the HIMET^{SM} technology designed and deployed for application to swine manure processing could provide substantial increases in methane output at swine livestock operations. For example, deployment of full scale HIMET^{SM} (with a 15 day HRT) at a hog operation with 10,000 animals (farrow-to-finish) could process the resultant manure stream of 106 m^3 or 28,000 gallons per day (assuming 5% total solids) to generate 1,600 m^3 or 56,400 ft^3 of methane per day. Conventional digestion (15 day HRT), on the other hand, would produce only 1,350 m^3 or 47,900 ft^3 of methane per day. In this case, two-phase digestion would have an energy generation advantage of over 250 m^3 or 8,500 ft^3 of methane per day, an 18% increase over conventional digestion.

6.2 Potential Biopower Advantages of the HIMET^{SM} Two-Phase Digestion Process Concept

For many applications of anaerobic digestion in the livestock industry, the generation of electricity represents the greatest source of cash revenue that can be realized from the waste-to-methane system. The manure-to-electricity technologies in use today are, in most cases, capable of yielding at least 30 percent more in electricity production than is currently possible. Conventional digestion technology that is used today in the production of electricity from swine manure and dairy manure typically consists of the use of single-stage un-mixed or limited-mixed digesters to produce biogas followed by the use of the generated biogas to produce electric power. At a moderate heating value of approximately 600 to 650 Btu/scf, the biogas is a limiting factor in the selection of generators which usually consist of internal combustion engines and microturbine prime movers; these generators are generally capable of limited performance from the standpoint of electricity generation efficiency, ranging from 22 to 28 percent.

Over the last several years, advancements in reciprocating engines have resulted in demonstrated heat rates of 8,200 – 9,500 BTU/kWh (37 to 42% efficiency) for engines of 250 – 1,000 kW size operating on natural gas. Capital costs for these engines have also improved to the $800-1100 /kW range. A few engine manufacturers have reported no de-rating of their advanced engines' performance when operating on biogas as long as the heating value of the biogas is consistently above 700 Btu/ft^3. This has been made possible through new engine and fuel supply system modifications, such as turbochargers and larger-capacity gas trains. These engine modifications can be realized at a minimal capital cost increase (3-5%).

In addition to the higher efficiency for electricity production, the new "packaged systems" offer other energy management benefits, as well, for swine farm applications. Heat recovery technologies coupled with prime movers as "packaged systems" can maximize the system efficiency and overall economics as well as limit labor costs associated with operating and maintaining such a system. Co-generated hot water reaching temperatures of over 88°C (190°F) offer opportunities for maximizing the utilization of waste heat for space conditioning of farm buildings/barns and enabling the use of emerging technologies for energy-intensive farm processes, such as low temperature ammonia absorption chillers and refrigeration (now under development at GTI). Site-specific commercial installations will need to deal with technical and institutional power grid interconnection issues and costs and back-up system requirements (i.e., dual-fuel propane/biogas engines and direct-fired absorption chillers).

The deployment of HIMET^{SM} two-phase digestion together with high-efficiency electricity generators can make substantial, overall improvements in electricity output and system economics for swine operations. Consider the previously-discussed example of energy generation from a 10,000 head hog operation (farrow-to-finish). The current baseline technology would consist of a combined phase anaerobic digester that produces a medium-Btu (650 Btu/ft^3) biogas (at a methane yield of 5.4 ft3/lb VS added) for utilization in a conventional internal combustion engine generator that produces electricity at an efficiency of about 28-30 percent. The advanced technology would consist of a two-phase anaerobic digester that produces a high-Btu (720 Btu/ft^3) biogas (at a methane yield of 6.2 ft3/lb VS added as achieved in this study) for utilization in a high efficiency reciprocating engine driven generator package that produces electricity at an efficiency of 38 percent. In both cases, about 105m3 or 27,600 gallons of manure (5% total solids) are passed through the digesters for energy production. The baseline system would yield about 16.6 million ft3 of methane per year that could support a 0.18 MW generator, producing 1.46 million kWh of electricity per year valued at $87,900 (assuming a 6 cents per kWh revenue stream).

On the other hand, the advanced system could yield about 19.6 million ft^3 of methane per year that could support a generator with a 0.26 MW power rating, producing 2.18 million kWh of electricity per year valued at $130,800. The overall boost in electricity generation potential from this facility would be increased by about 50 percent using an advanced technology enabled through the use of the HIMET^{SM} two-phase digester design. These energy generation estimates assume a stream factor of about 95%; in other words, it is assumed that the system will not be operating 18 days per year due to repair and/or maintenance.

6.3 Pathogen Control: A First Step to By-Product Recovery and Reduced Environmental Impact

The ability of anaerobic digestion to achieve the required reductions in pathogen indicators to achieve reliable compliance with the definition of a Class A biosolids is a critical initial step to achieving the overall goal of by-product recovery, water re-use and land application of the manure solids in a cost-effective manner that is protective of the public health and the environment. An example flow diagram of how HIMET^{SM} anaerobic digestion could be utilized to facilitate by-product recovery, water recycle, and waste solids reduction/disposal while improving energy benefits, is shown in Figure 6.1.

Through future process research and development, it may be possible to control and optimize the acid phase process to generate a high purity carbon dioxide stream that could be recovered for commercial use and to produce higher-molecular-weight volatile acids, fiber and other chemicals from the reactor mixed liquor contents. In extending the technology to animal operations that utilize bedding (e.g. dairy), recovery of bedding (sand or fiber) from this stage could be accomplished with little disruption to the biological process since acid forming bacteria are robust and not susceptible to inhibition due to the presence of trace oxygen which may occur in the mechanized bedding recovery operations. Future developments may also make it possible to recover the single cell protein from microbes that are grown within either stage of the HIMET[SM] process. Current wastewater separations engineering are already potentially capable of achieving certain types of recovery of water from digester effluents and conditioning of the water for effective reuse for manure flush system operations, though best practices in water handling to avoid animal stress due to ammonia accumulations may require some further development.

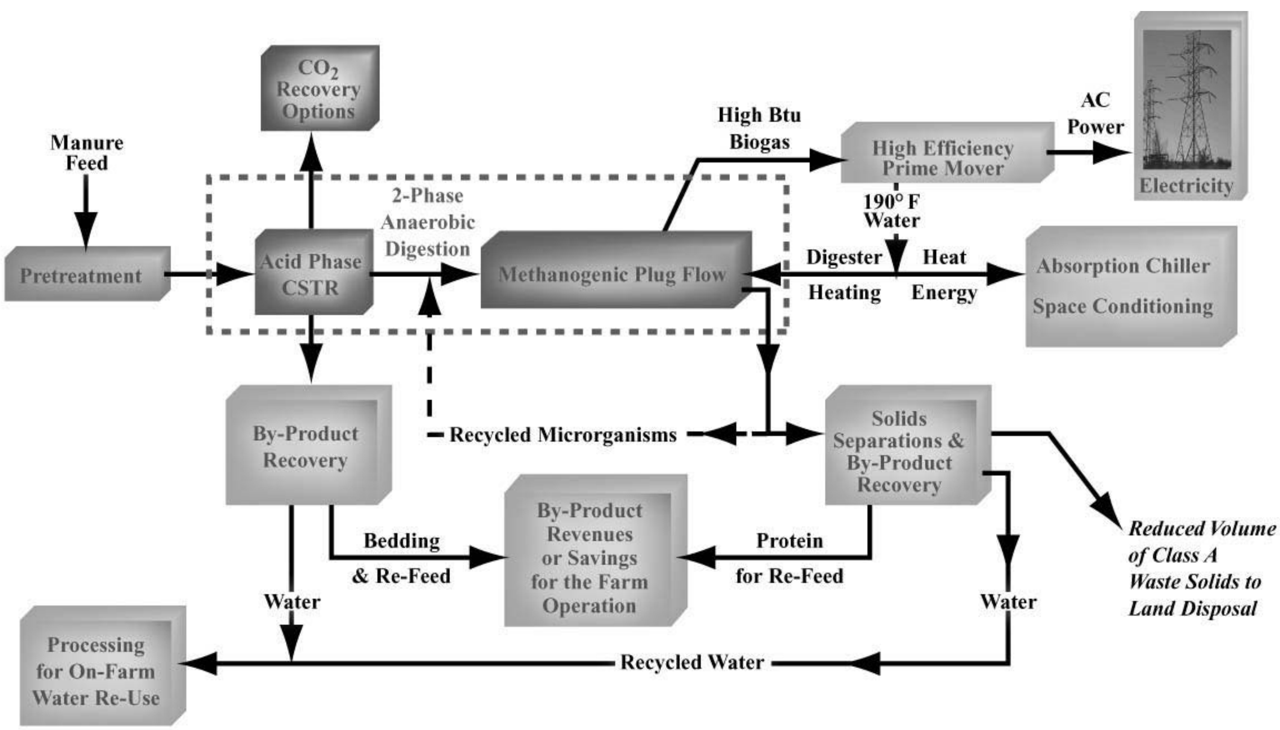

Figure 6.1 Options for the use of HIMET[SM] to improve energy, environmental and by-product benefits for swine operations

Whether pursuing the processing of solids for the recovery of refeed products for use in the animal operation itself or in other venture-oriented processes (such as aquaculture, fiber recovery, commodity fertilizers, etc.), or recycling water for flush-based mechanized manure removal, or generation of a reduced volume of solids that will be land applied, the potential risks (real or perceived) for water or solids to transmit disease or produce stress to animals and humans will be among the critical factors impacting the commercial feasibility of by-product recovery. In all of these cases of by-product recovery, it will be highly important that the streams that are processed and the products that are generated are reasonably free from disease-producing microorganisms and parasites.

As shown in the results of this project, HIMET^{SM} two-phase digestion technology has the potential of achieving highly efficient reductions and control over total coliforms, fecal coliforms and fecal streptococcus which are important indicators of communicable disease for animals and humans. For many intended uses of manures, mesophilic operation (35°C) may be sufficient to safely pursue by-product recovery and water recycle options. If additional protection is necessary, either stage or even both stages of HIMET^{SM} may be operated in the thermophilic mode at 55°C to provide further assurance of pathogen control to achieve the status of a Class A biosolids. While bacterial indicator data may be sufficient to demonstrate control of bacterial and viral pathogens, further research on the survival of parasites and fungi of concern may be desirable in the future to facilitate commercial deployment of by-product recovery options.

6.4 Preliminary Economic Analysis

Ultimately, the acceptance of and commercial success of anaerobic digestion at swine livestock operations will depend on the economic feasibility of the technology package for application to each specific site. The economics will depend upon a number of factors that are difficult to generalize for all swine operations. Swine livestock operations can vary in terms of layout, energy management needs, opportunities for electricity sales to the utility, manure management techniques planned for the site, etc; therefore the economics of biopower systems can vary from operation to operation. Key factors affecting biogas generation economics include scale of application, consistency of manure once it is collected, site selection, materials used for system design and construction, value of other benefits other than energy generation, residue by-product recovery, nutrient conservation, and dewatering to possibly achieve water re-use and to minimize manure handling and disposal costs. The purpose of this section is to provide a general economic estimation of the costs and benefits of applying HIMET^{SM} anaerobic digestion for the conversion of swine manure to biogas and electricity for a few example generic operations of varied size.

Much of the engineering experience in the design and costing of anaerobic digestion has been in association with municipal sewage treatment and with industrial waste management. In fact, over the last half century, the majority of anaerobic digesters in the U.S. have been constructed for the management of municipal and industrial sludges. In these markets, the paramount concern has been to reduce volumes of sludge requiring disposal ---- not to produce supplemental sources of low cost energy. Therefore, the directions of conventional anaerobic digestion process design for these markets has been dominated by sludge management objectives, including:

- Efficient sludge volume reduction
- Improved dewaterability
- Effective odor control
- Accessible for maintenance
- Durable structures that would extend plant life to 40+ years

To achieve these objectives, conventional digesters have been designed as above-ground, cylindrical tank structures, fabricated from steel reinforced concrete with rigid gas collection covers that were designed for extended life. Although this type of design was effective in meeting sludge treatment and disposal objectives, it was not conducive for producing economical biogas energy for a number of reasons:

- The conventional digester basins were expensive to construct with costs of up to $1,050 per m^3 ($4 per gallon)
- Conventional digesters required more heating for maintaining mesophilic or thermophilic temperatures because the majority of conventional units did not have sufficient insulation (if any at all)
- At hydraulic retention times of 40 to 60 days, the digesters were often underloaded (i.e. oversized) by a factor of two or three to promote digester stability amid the potential presence of heavy metals and other inhibiting chemicals that may enter the sewers and be concentrated in the sludges

Over the past two decades, much has been accomplished to overcome the high expense and the net energy production of conventional digestion. Comparisons of alternate structures with conventional digester materials indicated that earthen structures and certain farm-compatible equipment could potentially achieve large reductions in digester costs for applications to animal operations (Morris, et al., 1975). Subsequent development work on earthen structures to fabricate insulated and sealed digester basins led to a number of lower-cost, simplified designs that could be more economically applied to medium sized farms for biogas production (Jewell, et al., 1980). This effort identified low-cost approaches for building on-farm biogas systems, including the plug flow and random mix digesters, that could efficiently produce energy from dairy manure at reasonable capital and operating costs for farm operations.

The accomplishments of the alternate earthen farm designs led to the subsequent introduction of the plug flow digester design for commercial deployment of biogas systems at dairy and swine livestock operations in the U.S. over the last twenty five years. Detailed description of the construction of the plug flow digester from an earthen basin designed to minimize conducted and convective heat losses is described (Jewell, et al., 1980). A recent survey of the installed capital costs for the plug flow units indicates that most of these units have been installed at costs of less than $210 per m^3 ($0.80 per gallon) of reactor basin for digester systems with volume capacities of 1,100 to 1,900 m^3 (300,000 to 500,000 gallons); this cost is less than a quarter of the cost of conventional digestion (Lusk, 1998). Alternatively, fused-glass-lined bolted-steel tanks have also been deployed for manure digestion that have been reported to have an installed costs that are comparable to the costs of the earthen digester systems (Coppinger, et al., 1980).

In general, there are at least six major factors that will affect the site-specific economics of manure-based biopower systems:

1. Costs associated with the biogas generation system itself
2. Methane yield and output given the availability of manure feedstocks
3. The energy balance that provides a match between the forms of energy that are needed and those forms that can be produced
4. The investment required for the selected biogas utilization and biopower systems
5. Electricity generation efficiencies and the credits that can be taken as:
    - Avoided cost to the operation
    - Sale of electricity to a utility
6. Credits that can be taken for ancillary benefits of the biopower system, including:
    - By-Product Recovery
    - Waste heat utilization
        - Space conditioning
        - Absorption chillers
    - Environmental Compliance with CAFO Standards
    - Increased Productivity (from reduced animal stress and mortality)

For many cases, it is anticipated that electricity production will represent the greatest tangible opportunity to benefit the large-scale hog operation. Since two-phase digestion has the potential of increasing methane gas and electricity power output by 10 to 15 percent for swine operations, a cost-effective system may consist of a HIMET^{SM} biopower system constructed from some of the low cost materials currently used for on-farm biogas reactors. This type of system could consist of a small intermittently or randomly mixed acidogenic unit of hydraulic retention time (HRT) of about 1.5 to 3 days followed by a large methanogenic plug flow reactor with an HRT of 12 to 20 days. The list of construction components of a low-cost plug flow digester is described in the literature (Jewell, et al., 1980; Lusk, 1998).

A conceptual cost analysis of a HIMET^{SM} digester system was performed for a hypothetical swine operation of approximately 10,000 hogs (farrow to finish). The HIMET^{SM} system was assumed to consist of an intermittently mixed acidogenic reactor followed by a plug flow methanogenic digester. A list of the general components and component costs that can be used to estimate the capital cost for the advanced HIMET^{SM} system are presented in Table 6.2. Digester costs described in this table relate to the task of calculating the cost of biogas that could be made available for electricity production. The components of this table exclude the electricity generation equipment, since the economics of electricity generation are handled in a separate analysis. Total capital cost of the HIMET^{SM} biogas system for the 10,000 hog operation was estimated in this table to total $550,000. The capital cost for conventional digestion for the same scale of application was estimated at $1,216,800. With a total volume of about 1,570 m^3 (415,000 gallons), the major cause for the cost difference was the two-fold greater cost of the steel reinforced concrete basin comprising the conventional combined-phase digester.

The costs of constructing HIMET^{SM} for a 10,000 hog operations are described shown in Table 6.3 and compared to the projected costs of conventional digestion. Economic assumptions used in the analysis are presented in Table 6.4. Materials flow diagrams describing the performance of the biopower systems are shown in Figures 6.2 and 6.3 for the HIMET^{SM} and conventional digestion, respectively, as applied to the conversion of manure from 10,000 hogs to biogas and electricity. Performance of the conventional digester in terms of methane output and solids conversion efficiency are assumed to be comparable to the manure conversion results obtained for the combined phase reactor as described in this report. It was also assumed that the performance achievable with commercial scale HIMET^{SM} would be similar to the bench scale two-phase digester operated in this project on hog manure. If necessary, mixing could even be implemented in the low-cost, methanogenic, plug-flow second phase of the commercial-scale HIMET^{SM} system through the use of low cost intermittent recycle of the effluent to the influent sections of the digester. Materials for the conventional digester were assumed to be consistent with municipal construction methods. Materials for the advanced HIMET^{SM} unit, however, were assumed to be consistent with low cost techniques that have been developed and deployed for on-farm livestock biopower projects (Jewell, et al., 1980; Lusk, 1998; Legrand, et al.,1989).

ITEM	COSTS	BASIS
DIRECT CAPITAL		
Acid Phase Digester with cover	86,150	HRT = 3 Days Vol = 83,000 gallons Base Cost = $1/gallon
Methane Phase Digester with cover	208,900	HRT = 12 Days Volume = 332,000 gallons Cost = $0.80/gallon
Supplemental Tanks	29,510	For Surge Capacity HRT = 1 Day Vol = 28,000 gallons Base Cost = $1/gallon
Heat Exchangers	14,750	About 5% of the Digester Cost
Mixing Equipment	14,500	About 5% of the Digester Cost
Piping & Instrumentation	29,500	About 10% of the Digester Cost
Site Preparation	3,000	About 1% of the Digester Cost
Miscellaneous Equipment, Controls & Insulation	76,700	About 26% of the Digester Cost
Subtotal Direct Capital	**$463,010**	
INDIRECT COSTS		
Engineering	29,500	10% of Digester Cost
Construction Expense & Contingency	59,000	20% of Digester Cost
Subtotal Indirect	**$88,500**	
TOTAL CAPITAL	**$551,510**	

Table 6.2 Construction Cost Breakdown for the HIMET^{SM} Two-Phase Digester for the Production of Biogas at a 10,000 Hog Operation

ITEM	COSTS	BASIS
DIRECT CAPITAL		
Combined Phase Digester with cover	830,000	HRT = 15 Days Vol = 415,000 gallons Base Cost = $2/gallon
Supplemental Tanks	110,000	For Surge Capacity HRT = 2 Days Vol = 55,000 gallons Base Cost = $1/gallon
Heat Exchangers	29,000	About 5% of the Digester Cost
Mixing Equipment	28,000	About 5% of the Digester Cost
Piping & Instrumentation	83,000	About 10% of the Digester Cost
Site Preparation	8,000	About 1% of the Digester Cost
Miscellaneous Equipment, Controls & Insulation	215,000	About 26% of the Digester Cost
Subtotal Direct Capital	**$1,303,000**	
INDIRECT COSTS		
Engineering	48,500	6% of Digester Cost
Construction Expense & Contingency	59,000	20% of Digester Cost
Subtotal Indirect	**$88,500**	
TOTAL CAPITAL	**$1,410,500**	

Table 6.3 Construction Cost Breakdown for Conventional Digestion for the Production of Biogas at a 10,000 Hog Operation

Parameter	Value	Units
Initial Year of Plant Operation	2004	
Life of Long Term Equipment	30	Years
Life of Short Term Equipment	10	Years
Construction Period	0.5	Years
Construction Dollar Discount Rate	3.5	%
Inflation Rate	4	%
Fraction Financed by Debt	80	%
Fraction Financed by Non-borrowed Funds	20	%
Current Dollar Return to Debt	7	%
Current Dollar Return to Non-borrowed Funds	11.3	%
Tax Life Long Term Equipment	15	Years
Tax Life Short Term Equipment	5	Years
Investment Tax Credit	10	%
Working Capital Fraction	12.5	%
Stream Factor	95	%
Profit, % of Total Annual Capital and O&M	10	%

Table 6.4 Financial Assumptions

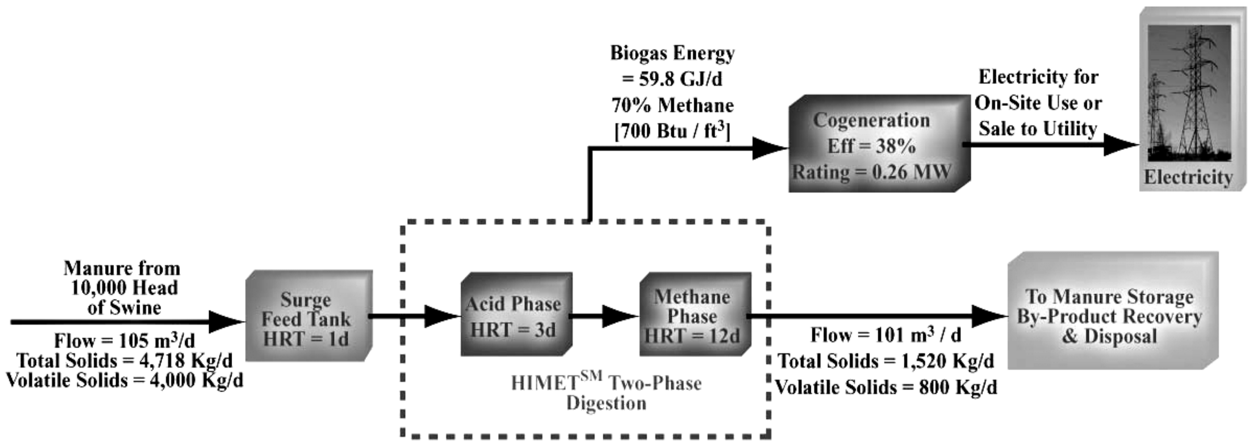

Figure 6.2 Materials flow analysis for HIMET^{SM} anaerobic digestion applied to a 10,000 head hog operation for the conversion of manure to biopower

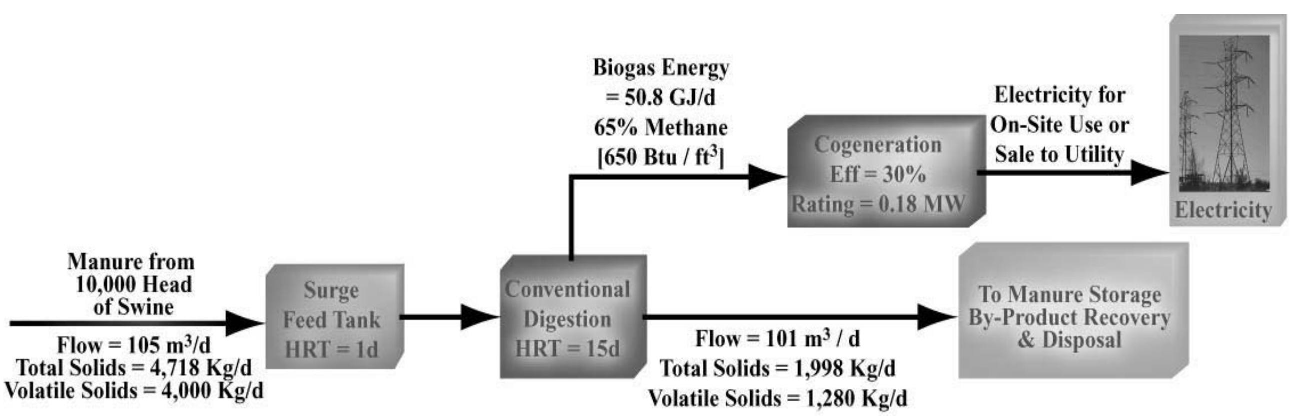

Figure 6.3 Materials flow analysis for conventional anaerobic digestion applied to a 10,000 head hog operation for the conversion of manure to biopower

The energy balances for both digester designs, were simplified by assuming that the two types of digesters could be heated using the waste recovered from the cogeneration of electricity in the form of a hot water stream with a temperature of at least 90°C (190°F). In each of these cases, no biogas was required for the direct firing of a boiler for purposes of process heating, though in the construction of the digester basins and covers, it was assumed that about 1 inch of insulation would be used to minimize conducted heat losses. Therefore, in the economic analysis of both of these digester technologies, the net methane production was assumed to be very close to the gross methane output.

The results of the economic analysis, as summarized in Table 6.3, show that the HIMET^{SM} technology can reduce the cost of converting swine manure to methane by more than 50 percent. In the example of the 10,000 hog operation, HIMET^{SM} was able to decrease the cost of biogas production from $7.38/GJ to $3.52/GJ. Each of these biogas costs would constitute a fuel gas cost component in the production of electricity in the flow schemes shown in Figures 6.2 and 6.3. The HIMET^{SM} gas cost of $3.52/GJ represents a fuel gas feedstock cost equivalent to about 3.3 cents per kWh, assuming a biogas-to-electricity conversion efficiency of about 38 percent can be achieved. On the other hand, the conventional digestion gas cost of 7.38/GJ represents a feedstock cost equivalent to about 8.9 cents per kWh, assuming an average biogas-to-electricity conversion efficiency of about 30 percent.

A more thorough analysis of the economics of biogas conversion to electricity and recoverable thermal energy that is of significant benefit to the hog operation would require a site specific inventory of energy needs and future challenges and goals for the facility in energy management. It does appear, however, that HIMET^{SM} offers considerable advantages in providing an economical biogas feedstock for electricity generation that is substantially lower in cost to produce compared to conventional digestion systems. Future engineering improvements that allow further reductions in the cost of digester construction and operational labor can potentially drive these costs even lower. Such improvements are anticipated as the experience and competition to apply biopower systems expands beyond the first half dozen facilities.

The scale of application of the HIMET^{SM} technology seems to be a major factor affecting the cost of biogas production. The relation of the size of hog operation versus biogas cost is shown in Figure 6.4. The plots of this graph included cost projections of the currently envisioned HIMET^{SM} system and cost projections of a HIMET^{SM} system that is optimized by future technology improvements that are achieved through R&D and progressive engineering design. Such improvements could include new construction techniques for the digester units or enhanced conversion of the manure through novel techniques of process control or solids management. One example of a future improvement might be the pre-concentration of the feedstock material through physical separation that would allow digester volumes to be decreased by as much as 50%. The technological improvements embodied in the "Optimized HIMET[SM]" technology are assumed in this diagram to be capable of reducing capital costs by 20% and reducing operational labor and maintenance costs by 15%.

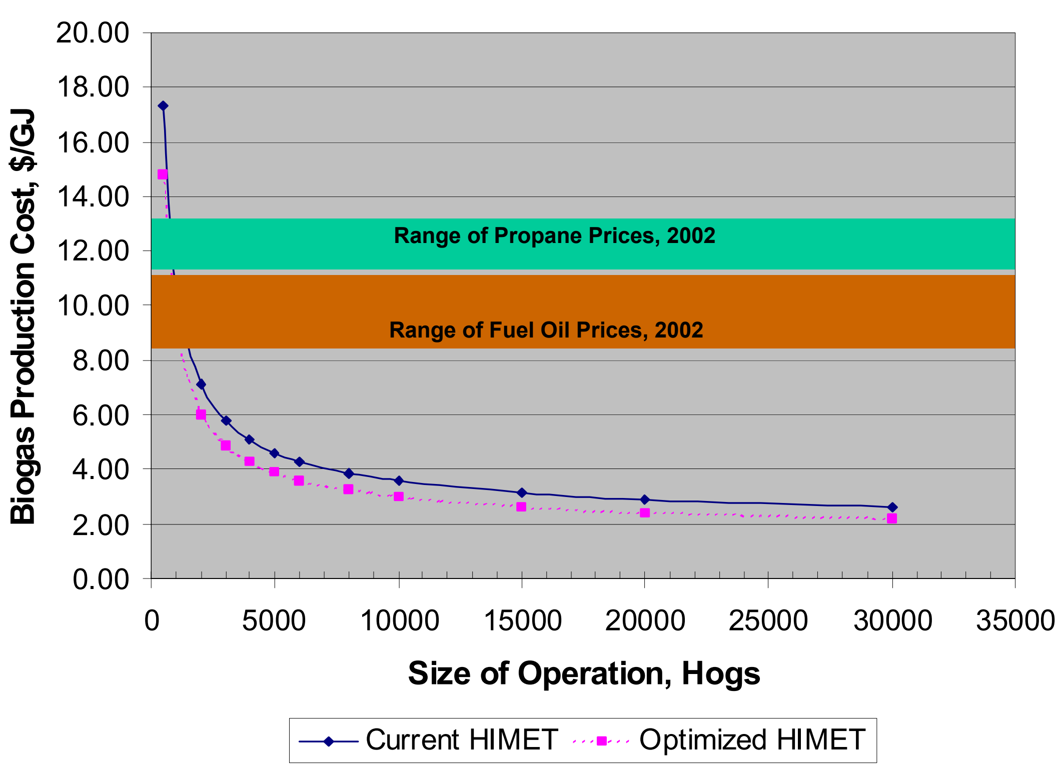

Figure 6.4. Biogas Energy Cost Versus Scale of Application

Also indicated on the graph of Figure 6.4 are the ranges of propane and fuel oil for comparison purposes. Propane and No. 2 fuel oil are the principal competing fossil fuels that are most commonly used on animal operations; these fuels represent the main competition for biogas utilization on hog farms. As shown in the diagram, the cost of producing biogas for both scenarios of HIMET[SM] deployment increases as the number of hogs at the facility decreases. The cost of biogas increases rapidly as the size of the hog operation falls below 1,000 hogs. However, even at the size of 1,000 hogs, biogas can be produced at a cost of about $10/mmBtu which is competitive with the 2002 prices for fuel oil ($8.25 to 11.00/GJ) and propane

($11.20 to 13.20/GJ). At facility sizes increasing from 2,000 to 10,000 hogs, the cost of biogas rapidly decreases and reaches a plateau of cost below $3/GJ. At very large sizes of 20,000 hogs and greater, it is projected that biogas can be produced with the HIMET^{SM} technology for less than $2.50/GJ, about 75-80% less than the cost of propane or fuel oil. This economic advantage makes HIMET^{SM}-produced biogas a potentially attractive alternative substitute feedstock for electricity generation for a wide range of swine operations.

If the total output of biogas can be used in a manner that displaces propane and/or fuel oil on the swine raising operation, the energy savings alone may justify the entire capital cost of the HIMET^{SM} digester system. A simple estimate of the payback period was performed for HIMET^{SM} based on the savings represented by the difference in annual costs for fossil fuel and the cost of biogas that would be used to replace fossil fuels. The capital cost of the HIMET^{SM} system was divided by the annual energy savings (assuming the composite fossil fuel displaced was valued at $10/GJ) to reach an approximate estimate of the payback period. The payback periods versus scale of application for HIMET^{SM} are plotted in Figure 6.5. Payback periods generally decreased as the scale of application increased. For the most likely scale of application between 3,000 and 10,000 hogs, the payback period is approximated at 3 to 6.5 years.

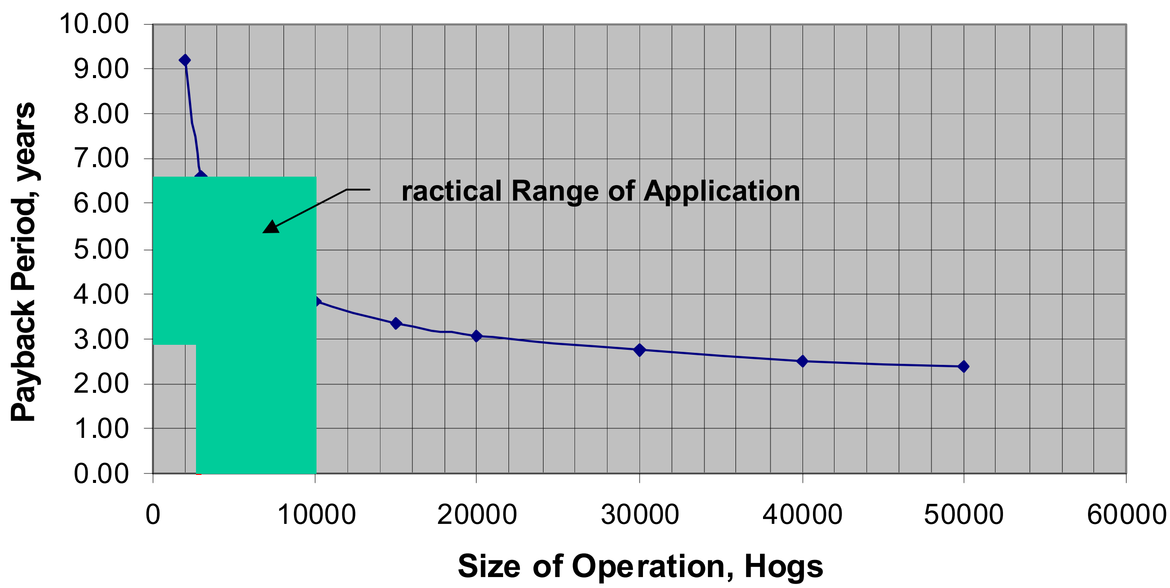

Figure 6.5 Payback Period Versus Scale of Operation

6.5 National Implications

On the national stage, anaerobic digestion can potentially provide substantial amounts of energy from livestock wastes. Within the U.S., if about a third of swine manure could be captured and converted to energy via anaerobic digestion, about 35 billion cubic feet (131 million m^3) of methane could be produced. At an average biogas-to-electricity generation efficiency of 30 percent, this amount of biogas could support a generation capacity of about 440 MW.

If anaerobic digestion could be extended to the efficient conversion of the wide range of manure resources available in the U.S., the energy generation benefits would be substantially increased. It is estimated that the total manure that is generated in the U.S. exceeds 300 million dry metric tons per year (counting wastes from cattle, poultry and swine operations) (Klass, 1998). If only 33% of this manure can be captured and if average conversion efficiencies of 60% (equivalent of 0.3 m^3 methane/dry kg VS) can be achieved, nearly 1.0 EJ per year of renewable methane energy can be produced, amounting to about 5% of the US natural gas demand. If all of this methane is converted to electricity at 30% efficiency, nearly 9,100 MW of electricity could be produced. Most of the manure targeted for anaerobic digestion would be based on the conversion of wet and often dilute manure (containing over 90% water) that would be difficult to process with thermal techniques but are best handled using a biological digestion method.

For each individual livestock operation, the introduction of advanced biogas end-use equipment and computer-based power management systems will maximize energy efficiency and energy-related revenue to the site owner. The use of HIMET^{SM} will enhance the heating value of the biogas to a consistent level over 700 Btu/scf, which enables the use of a new generation of high-efficiency cogeneration equipment for power, heating and cooling applications at swine operations. Customizing biogas utilization technologies to the energy needs of the livestock facility can be accomplished through the implementation of advanced cogeneration equipment, leading-edge adsorption/absorption cooling equipment, compressed gas storage and heat recovery systems. The continued trend in livestock operations toward larger and larger facility sizes and toward more automated and more centralized handling and storage of manure waste streams will provide better economies of scale for both biogas generation and biogas utilization.

The use of advanced biopower systems that enable electricity generation at efficiencies higher than 37 percent will result in a greater potential for the technology to boost distributed generation at livestock operations by more than 30%, nationwide. For example, the use of HIMET^{SM} digesters that enable biogas-to-electricity efficiencies to increase from 30 to 38 percent would boost the power generating potentials to 560 MW and 11,500 MW for swine operations and for the total manure resource in the U.S., respectively (again, assuming manure resource capture of 33 percent).

Another continuing trend is the rising interest of electric and gas utilities in the purchase of excess energy produced by livestock operations. A number of utility companies have already made commitments to obtain energy from non-fossil fuel sources, sometimes amounting to 10 MW or more. This demand for renewable "green energy" at reasonable prices will provide additional economic drivers for the commercial deployment of HIMET^{SM} for the anaerobic digestion of livestock waste.

7.0 Conclusion

A laboratory evaluation was conducted to determine the performance of two types of anaerobic digesters in the conversion of swine manure to biogas energy and to estimate the value of anaerobic digestion in providing environmental benefits to swine raising operations through pathogen control. The digester designs under evaluation included the conventional completely-mixed, combined-phase digester and the two-phase digestion process that is commercialized by the Gas Technology Institute under the name of HIMET^{SM}. Both processes were tested on hog manure and on sewage sludge which was used as a control feedstock. Two categories of information were collected: 1) process performance information on the conversion of the swine manure feedstock to biogas energy; and, 2) the potential of the HIMET^{SM} technology to reduce concentrations of manure-borne disease organisms when the digester system is operated in the mesophilic (35°C) and thermophilic (55°C) modes.

Testing of the digesters was conducted over a ten-month period. Results from the bench scale tests indicate that both HIMET^{SM} and conventional digestion can provide good efficiencies of conversion of the manure to biogas energy. However, the comparative evaluation also showed that the performance of HIMET^{SM} is superior to conventional digestion in terms of methane yield, reactor stability, and biogas quality. Specific conclusions are as follows:

1. Anaerobic digestion can convert swine manure to methane at a 50 percent higher conversion efficiency than observed for sewage sludge.
2. In the conversion of swine manure and sewage sludge feedstocks to methane, initial laboratory testing indicates that two-phase HIMET^{SM} digestion exhibited superior performance over conventional combined phase digestion in terms of methane yield and Btu content of the biogas.
3. HIMET^{SM} was able to achieve an average methane yield of over 0.39 m3 per kg of volatile solids added (6.2 ft3 per lb of VS added).
4. HIMET^{SM} was able to achieve an average manure volatile solids conversion efficiency of about 80 percent.
5. HIMET^{SM} was able to consistently produce a biogas of higher-Btu value, with a heating value well above 700 Btu per ft3. This consistency of high heating value would enable the use of advanced commercial generator packages (e.g. reciprocating engine driven cogeneration systems) that increase electricity generation efficiencies from the 25-30 percent levels of conventional systems to the range of

37 to 42 percent. This effectively increases electricity output by more than 30 percent.

6. HIMET^SM^ operated in the mesophilic mode (35°C) was able to achieve reductions in microbial indicators for pathogens by over 99.5 percent.
7. When operated in the thermophilic mode (where the methane phase was operated at 55°C), HIMET^SM^ was able to achieve reductions in pathogenic indicator organisms down to non-detect levels. This performance in pathogen reduction would likely produce a consistent Class A biosolids material that would be suitable for by-product recovery or for land application.
8. When configured and designed for biopower applications to swine raising operations, the HIMET^SM^ system is less than half the cost of conventional digestion in terms of capital cost and in terms of levelized (capital-amortized) per-unit cost of biogas produced. For example, the cost of biogas generation with HIMET^SM^ applied to a 10,000 hog operation is approximately $3.50/GJ compared to over $7.40/GJ for conventional digestion.

This project has shown that efficient conversion (>80 percent) of swine manure to biogas energy is technically feasible using two-phase HIMET^SM^ anaerobic digestion. This can be accomplished while achieving treatment conditions that can consistently produce a Class A biosolids material that can be safely processed for water recycle and by-product recovery. The following are recommendations for future research and development:

1. Determine the performance of HIMET^SM^ at pilot scale at various swine raising facilities to determine the effect of site specific feed variations and conditions on overall biogas output and solids conversion.
2. Develop and expand the options for by-product recovery, including refeeding, fiber recovery, and nutrient management.
3. Verify the potential of treated swine manure for achieving comprehensive control of disease organisms including vectors (e.g. fly populations), viruses and parasites.
4. Examine sludge separations processes and water treatment and conditioning for the economical recycle of water for automated manure handling and removal while improving control of indoor air quality for swine herd populations.
5. Demonstrate integrated biopower applications to specific swine raising operations. This would include the use of anaerobic digestion together with generator packages and waste heat management systems to meet on-site demands for electric power, heating and cooling.

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9.0 Appendix

Weekly Summaries of Digester Operation and Performance