This is to certify that the
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IMPACT OF SAND MANURE SEPARATION ON
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Impact of Sand Manure Separation on Anaerobic Digestion

By

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ABSTRACT

Impact of Sand Manure Separation on Anaerobic Digestion

By

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Bedding dairy cows on sand improves animal health resulting in higher milk production and overall farm profitability. The resulting sand-laden dairy manure (SLDM), however, complicates manure management, causing premature equipment wear, clogging pipes and settling during storage. Sand separation systems (SSS) remove and reclaim sand from SLDM. The increased handling of manure and the addition of dilution water associated with the removal of sand alter the manure characteristics. Efficiency of sand separation and the resulting impact on anaerobic digestion (AD) has not been extensively evaluated.

The objective of this research was to determine the impact of sand manure separation on AD. To accomplish this objective, a technique to estimate separation efficiency first needed to be developed. The separation efficiency of sand, in combination with an understanding of the residual sand characteristics and the loss of volatile solids (VS), allows for solid's balances to be determined across the entire sand separation system (SSS) and AD. This balance can then be used to predict impact on AD performance. To verify the predictions, comparison to a full-scale, operating digester was conducted.

Mass balance was found not found to be possible due to the unstable flow rates of several SSS inputs and outputs. Consequently, a semi-empirical

evaluation technique was developed that required a combination of industry standards and on-farm measurements. For the test farm, Green Meadow Farms, the overall fixed solids (FS) separation efficiency of 91 to 99% was estimated.

The average sand particle size remaining in the manure following the SSS, residual sand, was determined to be between 0.18 mm and 0.21 mm. Installed mixer power, theoretically could achieve the scour velocity for the residual sand average particle size, indicating that settling should be minimal. This was confirmed when one AD tank was emptied after fifteen months of operation revealing only 25 to 50 mm of sludge (sand and manure solids) accumulation.

During the sand separation process, a loss of VS from the manure stream was observed, however the change was not found to be a statistically significant treatment effect. The observed cumulative change in the mass of VS determined using the semi-empirical mass balance ranged from 33 to 53%. Changes in VS are important due to the direct correlation between VS and biogas potential. The theoretical electrical energy potential of the full-scale AD at the case study farm, which utilized SSS effluent as the feedstock, was 5,890 kWh/d. In 2008, the maximum electrical output of the full-scale system was achieved in July, when 5,505 kWh/d was produced or 93% of theoretical potential. The lost electrical generation revenue due to loss of VS throughout the SSS, assuming $0.08 kWh, was $123,200 per year.

Dedication

To My Wife Andrea and My Family

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ABBREVIATIONS

A	Area
α	Significance level
Acc	Acceleration
AD	Anaerobic digestion or anaerobic digester
AU	Animal unit
B	Constant describing condition of sand in channel
BMP	Biochemical methane potential
BP	Biogas potential
Btu	British thermal unit
CCUS	Counter-current upflow separator
C_d	Drag coefficient
Cp	Specific heat
Cp_s	Specific heat of sand
Cp_w	Specific heat of water
cP	Centipoise
D	Depth
d	Diameter
dF(x)	Mass flow of the influent
$dF_f(x)/dx$	Mass flow of the fine effluent
$dF_c(x)/dx$	Mass flow of the coarse effluent
e	Residual term

E_T	Overall separation efficiency
ϕ	Shape factor
f	Darcy Weisbach friction factor
F	Force
FS	Fixed solids
g	Gravitational acceleration
GMF	Green Meadow Farms, Inc
H	total heat
HC	Hydrocyclone or cyclone
hp	Horsepower
L	Liter
μ	Dynamic / absolute viscosity
M/m	Mass
m_{ash}	Sample mass after igniting
M_c	Mass of the coarse particles contained in the underflow
m_{dry}	Sample mass after drying
M_f	Mass of the fine particles contained in the overflow
m_{sample}	Initial (wet) sample mass
M_s	Mass of sand
M_w	Mass of water
Machine	Individual machine at a treatment level
MC	Moisture content
MDF	Minnis Dairy Farm

mgt	Farm management
MINI	Settling basins at GMF that follow SMS
min	Minute
MSU	Michigan State University
m_x	Daily manure production per cow
N_R	Reynolds number
O	Overflow flow rate
PD	Percent difference
PGS	Passive gravity separator
PSD	Particle size distribution
P	Power
Q	Flow rate
ρ_x	Density of material
r	Radius
rpm	Revolutions per minute
s	Specific gravity
$\Sigma_{influents}$	Sum of all material entering the device
$\Sigma_{effluents}$	Sum of all material exiting the device
SAS	Statistical analysis software
SLDM	Sand-laden dairy manure
SMS	Sand manure separation
$S_{n,\ acc}$	Mass of sand sample accumulated on the n^{th} sieve
SSS	Sand separation system

t	Time
T	Temperature
ΔT	Temperature difference
trt	Treatment
TS	Total solids
u	Overall mean
U	Unferflow flow rate
Unit	Level or machine within a sand separation system
v	Mean fluid velocity
VS	Volatile solids
$VS_{Conversion}$	Volatile solids destroyed in AD
V_h	Scour velocity
V_s	Settling velocity
V_x	Volume of a material
W	Width
wb	Wet basis
$X_{n, acc}$	Mass of total sand sample accumulated on the sieve of interest and all larger sieves
y	Response variable

CHAPTER 1: INTRODUCTION

Sand is the preferred bedding material at many dairy farms in Michigan and around the United Sates. As an inorganic bedding option, sand drains well, is less likely to harbor mastitis-causing organisms, reduces lameness, increases milk quality and production, provides traction in alleys and freely adjusts allowing even distribution of the cow's weight (Stowell and Inglis, 2000; Cook and Nordland 2004b).

Sand bedding mixes with manure resulting in sand laden dairy manure (SLDM). SLDM is difficult to manage as it clogs pipes, causes premature equipment wear, settles during storage and limits manure management options (Gooch, et al., 2002). Overcoming these limitations is essential for dairy farms to successfully manage manure.

1.1 Development of sand manure separation technologies

Prior to the development of sand separation technologies, SLDM was typically handled by daily scrape and haul (land application). Due to the volume of manure produced by an average dairy cow, 68 L/d (American Society of Agricultural and Biological Engineers, 2005), reliance on daily scrape and haul is difficult and inconvenient as it is dependent on weather conditions and land availability during the growing season. This lead many dairy farmers to construct long-term manure storages to provide flexibility in its management. However, during long-term storage, with the addition of dilution water from the milking center or precipitation, sand settles, accumulating as grit. Settled sand is not easily re-suspended into the manure slurry by agitation and often requires excavation. To facilitate excavation, long-term storages were constructed with concrete access ramps and floors, adding considerably to capital costs. Over time, operators developed a skim and haul technique, where the liquid fraction of the stored manure is pumped off allowing a longer interval between excavations. However, time and costs led producers to seek alternatives.

One such alternative is the sand manure separator (SMS), developed in the mid 1990's (patent number 5950839). Grit separation technology from the mining and wastewater industries provided the development platform (Wedel, 1995). Based on aerated grit chamber principals, sand is separated in the SMS in four steps: metering, agitation or turbulence, sedimentation and grit removal (Wedel and Bickert, 1996). Metering and dilution free sand from manure allowing the dense sand particles to settle. The lighter manure solids remain suspended in the liquid manure. Other separation technologies include the passive gravity-settling basin (PGS), sand lane and hydrocyclone (HC) (Wedel, 1995), further details in section 2.4.

1.2 Sand-free manure

Social and environmental concerns with modern dairy farms are leading to the development of innovative manure treatment technologies to improve nutrient utilization, diminish the potential for water pollution, reduce odor and emissions, decrease the cost and time associated with manure land application and potentially create discharge quality water from manure. However, the complex, mechanical nature of these technologies, requires manure entering the system to be virtually sand free.

Anaerobic digestion (AD), as part of an integrated manure management system, addresses many of these concerns including decreasing odor and emissions, lowering of water pollution potential by reducing the biological oxygen demand (BOD) and pathogen load, converting manure nutrients to more plant available forms and creating biogas, a source of renewable energy. Between 1981 and 1985 six-digester system were installed in Michigan (Rozdilsky, 1997). However, for technical, economic and managerial reasons, by 1990 only one of the original six AD was operating. Technological improvements and interest in odor control, energy generation and bio-fiber bedding production from digested manure solids is leading to renewed interest in digestion. According to the AgStar Program in 2008, there were 121 farm based AD operating in the United States with six in Michigan (U.S. Environmental Protection Agency, 2009). The majority of the US systems are on dairy farms that use organic bedding (shavings, sawdust or bio-fiber).

Operating data indicates that the performance of commercial anaerobic digestion systems, biogas yield as well as generator size and output, are highly variable and site-specific (Cornell, 2009). Seldom are changes in the VS content of manure due to manure collection, conveyance and pretreatment identified. Specifically, the impact of sand manure separation on the mass of volatile solids in the manure stream has not been well evaluated with Inglis et al. (2006)

completing the first document literature evaluation. Currently, only three digesters systems are operating on farms using sand bedding; Green Meadow Farms, Fair Oaks Dairy and Bridgewater Dairy. As greenhouse gas emission and renewable energy become increasingly important for regulatory and economic reasons, fully understanding the impact of bedding and manure management prior to anaerobic digestion will become crucial.

According to the American Society of Agricultural and Biological Engineers (2005), manure production from a lactating dairy cow is 68 L/cow/d. Midwest Plan Service (2000), reports that sand-bedding usage averages 22.3 kg/cow/d, equivalent to 13.1 L/d, which is significant when compared to manure. Accumulation of residual sand in the AD tanks is a primary reason why digesters are not more prevalent on sand bedded dairy farms (Inglis et al., 2006). If AD is used, the goal of sand manure separation shifts from removing enough sand to alleviate settling downstream and reducing wear on equipment. Sand-free manure is defined in this research as containing only residual sand that will remain suspended as it passes through units associated with AD systems.

The importance of sand-free manure to AD drives the need for techniques to quantify sand separation efficiency and to characterize the residual sand that passes through. This residual then needs to be correlated to the performance of the AD.

1.3 Research farms

Research was conducted at two commercial dairy farms, Green Meadow Farms, Inc., (GMF) and Minnis Dairy Farm (MDF). Both use similar sand separation equipment.

1.3.1 Green Meadow Farms

Green Meadow Farms operated one of the original six Michigan AD from 1983 until 1990 (Rozdilsky 1997). In 1990, the original AD was decommissioned due to mechanical issues with heating, sand accumulation and building decay. Removal of it, sand, which accumulated in the plug flow digester, required a complete system shut down resulting in significant labor cost and lost revenue due to a lack of biogas production.

In 1998, GMF installed four of the first commercially available SMS (Wedel, 2009) at their new 2,000-cow Farm 2. The sand separation system (SSS), and associated SMS, was installed to minimize equipment wear and prevent clogging and settling in downstream units. Each SMS has an integrated passive settling basin (MINI) to capture residual sand in the SMS effluent, resulting in a two level SSS. At this farm, all manure (SSS effluent) and milking center wastewater was transferred via single force main to a solid-liquid separator, which removed coarse manure solids from the slurry stream. Separated manure solids were composted or land applied while liquid manure was contained in long-term storage (180+ days) until it was land applied by irrigation.

In 2001, Farm 3 was constructed at GMF. To manage the manure from the additional 1,200 lactating and dry two additional SMS-MINI combinations were added. Shortly thereafter, a chemical phosphorus separation system was installed which used chemical precipitation and coagulation followed by flocculation and a belt filter press to remove phosphorus and manure solids from the manure stream. This resulted in a liquid fraction low in phosphorus such that it is irrigated growing crops and used as dilution water for the SSS. The solid material contains high phosphorus levels and is land applied.

Over the first seven years of operation, 1998 to 2005, the SSS performed well. However, sand did cause premature wear on the transfer and chemical phosphorus pumps, settled in pump chambers requiring regular excavation, occasionally clogged force-main lines and accumulated in long-term storages (Green, 2008). Quantitative measurements of the separation efficiency of the original SSS were not conducted however; Wedel and Bickert (1998) reported a separation efficiency for this general type of system in the range of 80% and 90%.

Because of the lack of data and experience in digesting manure from a farm that uses sand beddings, MSU researchers partnered with GMF in 2005 to develop a research/demonstration AD system to treat liquid manure from Farms 2 and 3. The project was largely funded by the Michigan Public Service Commission (MPSC). GMF was interested in AD because for odor control, potential of chemical cost reductions in their chemical phosphorus separation system, and revenues associated with the production of renewable energy, including carbon credits. Following the decision to install an AD, the goal of the SSS changed to creating sand-free manure. Consequently, a third level of separation technology was added to the system, a hydrocyclone (HC). The HC size and configuration was determined by the manufacturer and installed by GMF staff in 2006.

1.3.2 Minnis Dairy Farm

Minnis Dairy Farm is a 600-cow dairy that uses sand bedding. A two-level SSS that consisted of a single SMS and HC was installed in 2005. Unlike GMF, the SSS at MDF was installed with the goal of removing and reclaiming sand for reuse as bedding. MDF does not employ an AD. Since the installation of the SSS, residual sand has not accumulated in downstream units, however, the stainless steel dewatering screen and screw of the solid-liquid separator shows premature wear.

1.4 Research objectives

Dairy farms, in general, are unique facilities with varying management styles which combine to create site-specific manure management systems. Operation of these systems results in site-specific manure properties which should be considered when evaluating advance manure management systems, such as AD. Quantifying the site-specific impact of manure pretreatment (management) is important during the design of AD systems as the size of the tank(s), heating system and biogas utilization may be impacted. Improperly sized equipment can impact the system performance and cost the operator significant time and capital to remedy. Green Meadow Farms and Minnis Dairy Farm were used as case studies for testing techniques to quantify sand separation efficiency. Additionally, data from the operation of the AD at GMF was used to determine important design and performance considerations for dairy farms using sand bedding.

The specific research objectives follow.

1. Develop a technique to quantify the efficiency of sand separation systems.
2. Evaluate the residual sand particle size distribution to determine the potential for settling in anaerobic digester tanks.
3. Quantify manure volatile solids changes resulting from sand separation.
4. Determine the impact of sand separation on anaerobic digester performance (mixing, heating and biogas potential) and revenue potential.

Solids data from GMF was originally collected with the intent of determining the efficiency of the SSS as plans were being developed to install an AD that would utilize SSS effluent as feedstock. Performance of the SSS was critical to predicting sand accumulation in the AD tanks. Fixed solid (FS) were used to track SSS efficiency. During sample analysis for FS, volatile solids (VS) are also determined. While evaluating the FS data, it was observed that the VS data also provided insight into changes in the mass of VS throughout the SSS. This observation led to the development of objectives 3 and 4 and a shift in the focus toward determining the impact of sand separation on anaerobic digestion.

CHAPTER 2: Review of Literature

The following literature review examines the characteristics of manure, freestall-bedding options, the development of SSS, methods for determining SSS efficiency and the impact on the theoretical design of an AD system.

2.1 Manure production and characteristics

Manure production for lactating dairy cows is predicted to be between 67 and 68 kg/cow/d by American Society of Agricultural and Biological Engineers (2005) and Midwest Plan Service (2000), respectively. Dry cow manure production was estimated to be between 38 and 52 kg/cow/d (American Society of Agricultural and Biological Engineers, 2005; Midwest Plan Service, 2000). American Society of Agricultural and Biological Engineers (2005) estimates for manure and nutrient excretion were derived from the combination of multiple data sets from Washington State University, University of California – Davis, The Ohio State University, and Pennsylvania State University. Both sources define manure as the combination of feces and urine with no addition of water or bedding. Midwest Plan Service (2000) indicated that actual characteristics of manure could vary ±30%.

Moisture content of lactating and dry cow manure was similar for both references, ranging from 87% to 88% (American Society of Agricultural and Biological Engineers, 2005; Midwest Plan Service, 2000). American Society of

Agricultural and Biological Engineers (2005) determined the total solids (TS) excretion for a lactating and dry cow to be 8.9 and 4.9 kg/d/cow, respectively. Volatile solids (VS) excretion was found to be 7.5 and 4.2 kg/d/cow, for a lactating and dry cow respectively (American Society of Agricultural and Biological Engineers, 2005). The difference in TS and VS is the fixed solids (FS) (Wedel, 1995).

Nennich et al. (2006) and Bannink et al. (1999) reported that the mass of urine was approximately one-third of the total mass of manure excreted daily. The TS concentration of urine ranges from 3% to 4.5% (American Society of Agricultural and Biological Engineers, 2005; Bannink et al., 1999). Urine volume and composition is variable depending on ration, mineral supplement, lactation stage and environmental conditions (American Society of Agricultural and Biological Engineers, 2005).

2.2 Freestall bedding and cow comfort

Animal health, cow comfort and milk production are advantages of sand bedding, compared to organic bedding (Inglis et al., 2006; Wedel, 2001). However, the production of SLDM limits the options available for manure collection, conveyance, treatment, storage and utilization (Wedel and Bickert, 1996). Advance manure treatment technologies are particularly susceptible to operating problems if sand is in the manure stream (Wilkie, 2005; Rozdilsky, 1997). Separation of sand from manure, resulting in an effluent that is essentially sand free, is crucial for the successful adoption of AD and other advance treatment (Inglis et al., 2006).

Cow comfort is an important management component of production and overall animal health (Wagner-Storch et al., 2003). Studies show that cow comfort impacts milk yield and quality as well as animal health and longevity (Linn, 2001). Bedding type is an important factor contributing to cow comfort. Freestall bedding material should provide a clean, dry surface (Bewley et al., 2001). Karszes (2003) added that properly designed and maintained freestalls minimize the potential for mastitis, reduce hock abrasions and limit injuries to animals. Freestall bedding materials are generally categorized as organic or inorganic.

Common organic freestall bedding materials include crop residues (straw and corn stalks), wood biomass (sawdust and shavings) and recycled material (separated manure solids and newspaper). Cost and availability generally determine which organic bedding is used on organically bed dairy farms. To reduce bedding usage and costs, concrete, rubber mattresses or rubber pillows (filled with a variety of materials) are sometimes used to create the freestall base on farms using organic bedding (Cook et al., 2004; Bewley, et al. 2001). Another advantage of manure containing organic bedding is that it requires little to no pretreatment prior to treatment or storage. Manure collection and conveyance on dairies using organic bedding consists of scrape or flush collection with gravity flow or pump conveyance. Conventional clay-lined, concrete or steel manure storages are used for manure containing organic bedding.

Disadvantages of organic bedding include harboring mastitis causing microorganisms, absorption of water, urine and milk, and slippery freestall alleys. Rubber mattresses and hard surfaces also have disadvantages. Cook et al. (2004) found that dairy cows spend significantly more time standing in freestalls with rubber mattresses than cows housed in barns that use sand bedding. Extended standing time and firm or hard freestall-bases increased the number of lameness cases, compared to sand (Cook, 2003). Cook (2001) estimated that the average cost to treat lameness on dairy farms using organic bedding was $82.50/cow (2001 dollars) compared to sand based dairy farms.

Sand is the most common inorganic bedding. Others options include crushed limestone and byproducts from industrial manufacturing. Sand has been promoted as the "gold standard" bedding material because it is non-hygroscopic, drains well, provides traction in alleys, is less likely to harbor mastitis-causing organisms and moves freely allowing even distribution of the cow's weight (Stowell, 2000;Bernard and Bray, 2004).

Inorganic sand bedding results in an increase of 1.4 to 1.8 kg/d of milk production compared to organic bedding materials (Stone, 2003). Likewise, herds on sand bedding typically have milk somatic cell counts (SCC) 50,000 cells per milliliter less than comparable herds on organic bedding (Stone, 2003). Cook and Nordlund, (2004) determined that sand bedding created a $152 cow/yr (2004 dollars) advantage over organic bedding materials.

Positive benefits of sand bedding are balanced by the difficulties of managing sand in the manure stream. SLDM is abrasive, increasing wear and shortening the life of manure handling equipment (Stowell and Bickert, 1995). According to the Midwest Plan Service (2000), a typical mature dairy cow requires 8,130 kg/yr of sand bedding. In addition, SLDM is typically not stackable or pumpable (Wedel and Bickert, 1994). Bedding sand tends to settle out of suspension during conveyance, treatment and storage resulting in clogging systems and reduced capacity (Inglis, 2006). Sand that settles during storage is difficult to re-suspend and generally requires physical removal (excavation) with a loader tractor. To accommodate removal, manure storages are generally constructed with a concrete floor and access ramp. In order to reduce issues with SLDM, sand separation technologies have been developed to allow for the removal of sand prior to treatment or storage.

2.3 Sand separation technology development

Over the past two decades, significant advances have been made in the development of technologies for separating sand from manure (Wedel and Bickert, 1994; Wedel and Bickert, 1996; Wedel and Bickert, 1998; Wedel, 2001). Separation technologies from the mining industry and municipal and industrial wastewater treatment have been adapted (Wedel, 1995) to SLDM. Several separation techniques are used including screening, sedimentation, centrifugal force (hydrocyclone), dissolved air floatation and belt filter press with polymer addition (Wedel, 1995).

2.3.1 Factors affecting sand separation

All sand separation technologies rely on the basic principles of sedimentation (Wedel, 2001). Sedimentation is the separation of grit (heavy particles) from water by gravitational settling (Metcalf and Eddy, 1991). Performance of individual sand separation technologies and the overall sand separation system (SSS) is affected by several characteristics of SLDM including specific gravity, particle size distribution, viscosity and sand quantity (Wedel, 2001; Wedel and Bickert, 1996). Table 2.1 summarizes range of the various parameters impacting sand removal.

Table 2.1: Parameters impacting sand separation efficiency

Parameter	Minimum	Maximum	Unit	Reference
Absolute viscosity of manure (μ)	6	36,200	cp	Keener et al., 2006
Typical bedding sand size	0.076	2.01	mm	AASHTO, 1991
Specific gravity of sand	1.4	2.5		Glover, 1995 & Wedel, 2000
Specific gravity of manure	0.4	1.05		Glover, 1995 & Wedel, 2000

2.3.1.1 Fluid viscosity

Viscosity, the resistance of a fluid to deformation under shear stress (Steffe, 1996), is commonly used to describe the internal resistance to flow. Viscosity in terms of sand manure separation is important because high viscosity increases friction, slowing the rate of settling. A basic understanding of the rheological properties, physical and flow properties (Landry et al., 2003; Steffe, 1996), of dairy manure is needed to determining settling characteristics. Manure is a mixture of water and solids in a matrix of long chain organic molecules described as mucus (Wedel and Bickert, 1996). Mucus, a weak viscoelastic gel

(Allen et al., 1984), is commonly found in the gastrointestinal tract of dairy cows (Wedel, 2001). Manure exhibits non-Newtonian, shear-thinning properties (Wedel, 1995), where increasing the shear rate decrease the apparent viscosity (Steffe, 1996). Separation of sand from manure requires disruption of the mucus molecule (Wedel, 2001), this is accomplished by agitation and turbulence (Wedel and Bickert, 1996) which thins the material while the addition of dilution water is disperses the particles.

Mixing, time, temperature and pressure influence the viscosity of a fluid (Steffe, 1996). Kumar et al. (1972) reported that the viscosity of dairy manure decreased with increasing temperature. Viscosity is also influenced by the TS concentration of the slurry inside the SSS. Landry et al. (2003) found that apparent (dynamic) viscosity of manure is well correlated to the TS concentration. Keener et al. (2006) confirmed this finding and found that viscosity decreased exponentially as the moisture level increased. On dairy farms, TS concentration can be lowered through dilution (Kenner et al., 2006; Landry et al., 2003). For dairy manure as excreted, Keener et al. (2006) studied the change in viscosity and developed Equations 2.1 and 2.2, to predict dynamic viscosity based on moisture content and rotational velocity of the spindle (spindle speed).

$$\mu = e^{63.289 - 0.6211 * MC} \tag{2.1}$$

$$\mu = e^{58.218-0.570*MC} \quad \textbf{(2.2)}$$

MC = moisture content, %

μ = dynamic viscosity, cp

Equation 2.1 is based upon a spindle speed of 30 rpm, while Equation 2.2 uses a spindle speed of 60 rpm. Keener et al., (2006) used a rotary viscometer to measure viscosity. The rotary viscometer used a fixed cup and a spindle to measure the resistance of a fluid to flow. Trials were carried out at two temperature profiles 20°C and 23°C and over a range of moisture contents, on a weight basis (wb). The range of dairy manure apparent viscosity typically found on farms is shown in Table 2.2 for both spindle speed equations.

Table 2.2: Dairy manure dynamic viscosity range (Keener t al., 2006)

Moisture Content (wb)	Dymanic Viscosity (μ)		Average μ (cp)
	30 rpm @ 23°C (cp)	60 rpm @ 23°C (cp)	
85	36,152	17,466	26,809
99	6.1	6.0	6.0

2.3.1.2 Sand particle size

Sand particle size characteristics vary by location, mineral type and mining or manufacturing process (Gooch and Inglis, 2007). Bedding sand is a composite material comprised of particles of varying size, density and shape. Table 2.3 compares the soil particle size distribution of three common classification systems; United States Department of Agriculture (USDA), Unified and American Association of State Highway and Transportation Officials (AASHTO). All three-classification systems overlap with a sand particle size range of 0.08 mm to 2.0 mm.

Based on the USDA soil classification triangle, shown in Figure 2.1, to be classified as sand the material can contain a combination silt and clay that is no more than 10% of the total mass of the material.

Table 2.3: Comparison of sand particle size range from three common classification systems

Description	USDA (2008)		Unified (ASTM, 2006)		AASHTO (1991)	
	Min (mm)	Max (mm)	Min (mm)	Max (mm)	Min (mm)	Max (mm)
Very coarse sand	1.00	2.00				
Coarse sand	0.50	1.00	2.00	4.83	0.43	2.00
Medium sand	0.25	0.50	0.43	2.00		
Fine sand	0.10	0.25	0.08	0.43	0.08	0.43
Very fine sand	0.05	0.10				
Silt	0.03	0.05	0.08			0.08
Clay		0.03				

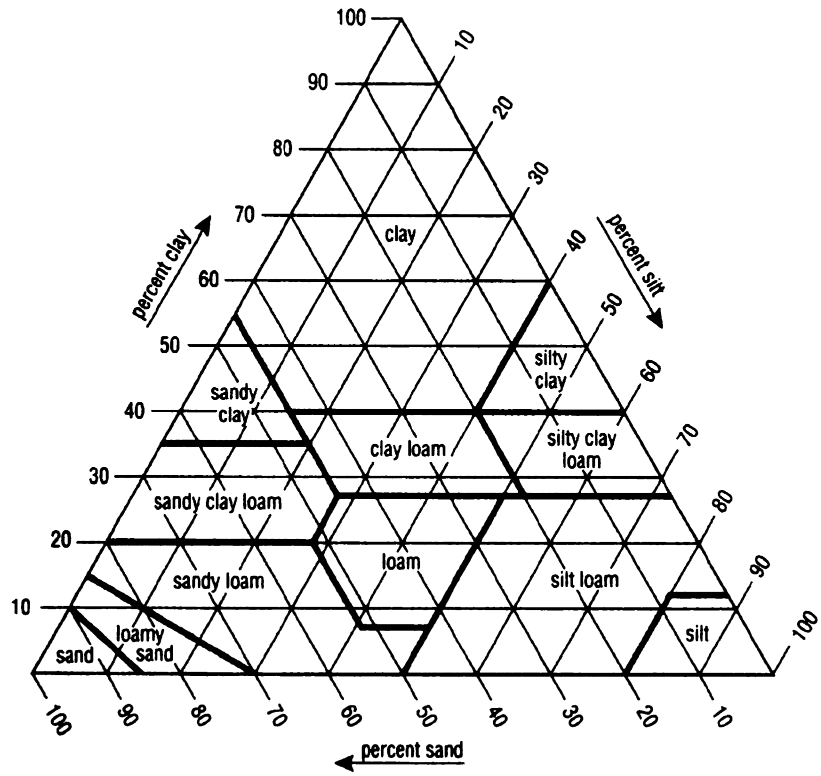

Figure 2.1: USDA soil classification triangle (USDA, 1993)

Concrete and Mason sand are construction categories by the American Society for Test and Materials (ASTM, 2006) as standards C-33 and C-144, respectively. These are common bedding sands used on dairy farms around the Midwest. Table 2.4 shows the high and low particle size limits established by ASTM for Concrete and Mason sand. Also, 2NS is a Michigan Department of Transportation (2003) standard that is commonly used for bedding sand on dairy farms in Michigan.

Table 2.4: Standard particle size distributions

US Standard Sieve #	Sieve Opening	Percent Passing				
		Concrete Sand (ASTM C-33, 2006)		Mason Sand (ASTM C-144, 2006)		2NS Sand
	(mm)	Low Limit	High Limit	Low Limit	High Limit	(MDOT, 2003)
4	4.75	100%	95%	100%	100%	98%
8	2.36	100%	80%	100%	95%	80%
16	1.18	85%	50%	100%	70%	55%
30	0.6	60%	25%	75%	40%	38%
50	0.3	30%	5%	35%	10%	20%
100	0.15	10%	0%	15%	2%	5%

Understanding the sand particle size distribution is critical to the development of a SSS because the diameter of the sand is needed to determine the settling and scour velocity. American Society of Civil Engineers (1975) indicates that particle size is the most important parameter, related to the sand grain, for predicting sedimentation. In addition, Zimmels (1984) stated that separation technologies are less efficient for wide distributions of particle size. Therefore, different separation technologies are effective over only a portion of the sand range.

2.3.2 Equations governing sand separation system design

Settling and scour velocity are the two most important parameters in the design of hydraulic conveyance and sand manure separation systems. The subsections below discuss each.

2.3.2.1 Terminal settling velocity

When a particle is released in a still fluid, it accelerate until the sum of the drag (upward) and the buoyant (upward) force equal the weight of the particle (downward) and the buoyant force (downward) (Liu, 2001), this phenomenon is known as terminal settling velocity (Wedel, 1995). Figure 2.2 depicts the force balance in a still fluid.

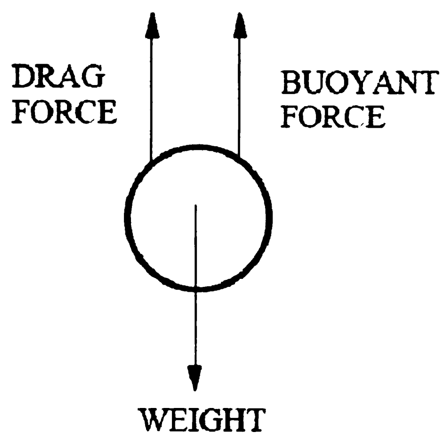

Figure 2.2 Force balance on a particle settling in a quiescent fluid (Wedel, 1996)

Particle size and density are two critical parameters used in calculating the terminal settling velocity (V_s) of a spherical sand grain using Stokes Law, Equation 2.3 (Lamb, 1993; Wedel and Bickert, 1996).

$$V_s = \frac{(\rho_p - \rho_f) * g * d^2}{18 * \mu} \qquad \textbf{(2.3)}$$

V_s = settling velocity, m/s

ρ_p = particle density, kg/m^3

ρ_f = fluid density, kg/m^3

g = gravitational acceleration, m/s^2

d = particle diameter, m

μ = dynamic (apparent) viscosity, kg/m · s

18 = particle area and drag coefficient correction factor

Stokes law holds true for flow fields with Reynolds numbers less than 0.5 (Camp, 1945; Metcalf and Eddy, 1991). The Reynolds number can be determined using Equation 2.4 (Metcalf and Eddy, 1991).

$$N_R = \frac{v*d*\rho_f}{\mu} \qquad \textbf{(2.4)}$$

N$_R$ = Reynolds number, dimensionless

v = mean fluid velocity, m/s

d = diameter, m

In addition, Stokes law assumes that settling particles are spherical. Settling velocity of non-spherical particles can be determined by a modification of Newton's Law (Gregory et al., 1999), which includes a terms for the particle drag coefficient and shape. Newton's Law is expressed in equation 2.5.

$$VS = \left(\frac{\frac{4}{3}*\frac{g}{C_d}*(\rho_p-\rho_f)*d}{\phi*\rho_f}\right)^{0.5} \qquad \textbf{(2.5)}$$

C_d = drag coefficient

ϕ = shape factor

The drag coefficient as expressed in equation 2.6 (Concha and Almendra, 1979).

$$C_d = 0.28 * (1 + \frac{9.06}{R^{0.5}})^2 \qquad \textbf{(2.6)}$$

Shape, the combination of sphericity and roundness, impacts the particle friction; angular particles are subject to more friction then rounded particles (Alshibli et al., 2004). Angular sand particles generate more friction during sedimentation processes than rounded grains. The result of the increase in friction is slower settling velocity for angular particles. Shape factor ranges from 0 to 1 for sand. Natural sand on average has a shape factor of 0.7 (Vanoni, 2006).

Table 2.5 compares the terminal settling velocity of sand and manure particles in liquid manure. Equation 2.5 was used to calculate the settling velocity of sand particles with a shape factor of 0.7 in a laminar flow (R=2,300) . Due to a lack of shape information, the settling velocity of manure was calculated using Equation 2.3 with a moisture content of 95%. For both, fluid density of manure was assumed to be 1,000 kg/m^3 (Table 2.1).

Based on the predicted values in Table 2.5, sand particles have a settling velocity at least 13 times greater than that of equal size manure particles. However, smaller sand particles have settling velocities similar to larger manure particles. For example, in Table 2.5, it can be noted that a sand grain with a diameter of 0.15 mm has a settling velocity similar to manure solids with a particle size of 4.75 mm. This indicates that coarse manure particles may settle with smaller diameter sand grains.

Table 2.5: Theoretical settling velocity of sand and manure particles in slurry (Camp, 1945)

Particle Diameter	Settling Velocity	
	Sand	Manure
(mm)	(m/s)	(m/s)
4.75	4.1E-01	3.1E-02
2.36	2.9E-01	7.7E-03
1.18	2.1E-01	1.9E-03
0.60	1.5E-01	5.0E-04
0.30	1.0E-01	1.2E-04
0.15	7.3E-02	3.1E-05
0.07	5.2E-02	7.6E-06

Settling velocity is a useful tool in determining sand removal because it account for particle size, density and fluid density. Simplified sediment transport models assume complete removal of all particles with settling velocities greater than the overflow rate of the sand separation device (Jin, et al., 2000). The determination of settling velocity is important when selecting bedding sand particle size. Based on Stokes Law (Equation 2.3), the ideal sand particle in terms of size and density should be a medium to coarse grain with a high density. Understanding the settling velocity of a particle is important, however, the energy required to resuspend (scour) a particle is greater and should be used to size mixing systems used on dairy farms with sand bedding.

2.3.2.2 Scour velocity

Scour velocity is the mean horizontal velocity necessary to impart motion on a particle at rest (Wedel, 2000). Similar to settling velocity, particle size and specific gravity of sand is critical to determining scour velocity. Shields' equation (Equation 2.7), as described by Camp (1945) and Crites and Tchobaboglous (1998), is used to determine the horizontal scour velocity of particles.

$$V_H = \left(\frac{(8*B*g*d*(s-1)}{f}\right)^{\frac{1}{2}} \quad \textbf{(2.7)}$$

V_H = scour velocity, m/s

B = constant describing condition of sand in channel

s = specific gravity

f = Darcy-Weisbach friction factor

8 = Darcy-Weisbach correction factor

The minimum scour velocity (initiation) will move particles by saltation, the forward movement of particles by bouncing along a surface (Wedel, 2000), while the complete scour velocity fully re-suspends particles. According to Wedel

(2000), the bed constant, B, ranges from 0.04 for scour initiation to 0.8 for full scour. Typical Darcy-Weisbach friction factors range from 0.02 to 0.03 (Metcalf and Eddy, 1991). The Darcy-Weisbach friction factor depends on the surface characteristics over which the material flows. Table 2.6 summarizes the range of scour velocities for a range of sand and manure particle sizes.

Similar to the settling velocity relationship, the initiation and complete scour velocities of manure solids is roughly one fourth that of an equal size sand grain (Table 2.6). The difference in the scour velocities of sand and manure is largely attributed to the difference in specific gravity, 1.76 for sand compared to 1.04 for manure.

Table 2.6: Theoretical scour velocity of sand and manure particles (sand: f=0.03 and s=1.76, manure: f=0.03 and s=1.04)

Particle Diameter	Scour Velocity			
	Initiation		Complete	
	Sand	Manure	Sand	Manure
(mm)	(m/s)	(m/s)	(m/s)	(m/s)
4.75	0.68	0.14	3.02	0.63
2.36	0.48	0.10	2.13	0.44
1.18	0.34	0.07	1.51	0.31
0.60	0.24	0.05	1.07	0.22
0.30	0.17	0.04	0.76	0.16
0.15	0.12	0.02	0.54	0.11
0.07	0.08	0.02	0.38	0.08

Interestingly, the velocity required for complete scour of manure particles is nearly equal to the initiation velocity of similar sized sand grains.

Camp (1945) suggested that the mean velocity within the SSS should not exceed the settling velocity of the largest sand grain to be recovered. Ideally, the velocity of the separation device would not exceed the settling velocity of the target sand particle, but would surpass the scour velocity of a majority of the manure particles. However, due to the similarity in sand grain settling velocity and manure solid initiation velocity it may not be possible to design SSS that can practically achieve the optimal velocity. For evaluation and design purposes, scour velocity is used to size mixing systems to minimize sedimentation.

2.3.3 Early sand separation research

Research conducted by Wedel (1995) found that sand does not settle out of suspension in undiluted raw dairy manure due to the high viscosity created by mucus and the variable and irregular shapes of the particles contained in the SLDM matrix. Wedel (1995) discovered that by diluting the manure with a little as 0.5 parts water to 1 part SLDM followed by agitation was sufficient to initiate the separation of sand, manure solids and water. Dilution dispersed the solids and mucus while agitation enhanced shear-thinning behavior, thus reducing the overall slurry viscosity.

Wedel (1995) conducted settling experiments in clear columns, at a dilution ratio ranging from 0.5 to 5 parts water to 1 part SLDM. The research found that at dilution ratios as low as 1:1 caused distinct layers of sand manure solids and liquid began to form (Wedel, 1995). Increasing the dilution ratio from

1 to 1 up to 5 to 1 significantly reduced the time required for sand to settle out of the SLDM mixture.

Hinder settling is the predominate type occurring in diluted SLDM. The other settling types are simultaneously occurring to a lesser extents (Inglis, 2006). As the dilution ratio increases, the SLDM mixture viscosity decreases transitioning the settling from hindered to discrete.

Hindered and discrete settling are two of the four particle settling classes, which include (I) discrete (or free), (II) flocculent, (III) hindered and (IV) compression settling (Metcalf and Eddy, 1991). Discrete settling occurs when individual particles settling without interaction or flocculation. Flocculent settling occurs when particles in a dilute suspension interact and aggregate, creating larger heavier particles. Hindered settling occurs in solutions with intermediate particle concentration. The particles density causes interparticle forces to fix each particles relative position, causing the mass of particles to settle at a constant rate. Suspensions with high particle concentrations result in particles touching and settling by compaction of the mass.

2.3.4 Sand separation goals

SSS is intended to remove sand from the manure to achieve different goals, as discussed below (Bickert and Kirk, 2007).

1. To remove most, but not all, of the sand from the manure stream with no intention of using the removed sand for bedding. Removal is just enough to reduce downstream problems.

2. To reclaim sand clean enough for reuse as freestall bedding.
3. To create a sand-free manure stream for downstream treatment as well as reclaim sand for reuse as bedding. Sand-free manure is critical for farms implementing advanced manure treatment systems such as anaerobic digestion.

Kappe and Neighbor (1951) reported that grit removal systems used to treat municipal wastewater captured a sufficient quantity of particles with a diameter of 0.2 mm. (U.S. Sieve No. 70) to effectively protect pumps from heavy wear and prevent deposits in downstream treatment units. Wedel and Bickert (1998) asserted that mechanical SMS remove between 80% and 90% of the sand contained in SLDM. Fulhage (2003) reported that settling basins removed between 71% and 75% of bedding sand. Both demonstrate that goal 1 is achievable.

Findings by Harner et al. (2005) found no difference in the bacterial concentrations of new (fresh) and 7 to 10 day old reclaimed sand, indicating that SSS could achieve goal 2.

Sand-free manure, goal 3, is defined as containing residual sand that does not settle during storage. Sedimentation chambers (settling basins) operating at municipal wastewater treatment plants have recovered up to 99% of grit with a diameter of 0.003 mm (US Sieve No. 200) (Wedel and Bickert, 1996).

2.3.5 Fundamentals of sand separation technology

For all three goals, successful separation of sand and manure is based on four key steps; metering, mixing, which includes agitation and turbulence, sedimentation and sediment (sand) removal (Wedel and Bickert, 1996). The intent of metering is to balance the input of raw SLDM in to the SSS so that the dilution and agitation capabilities are optimized. Improper metering can lead to poor sedimentation and reclaimed sand containing a high concentration of VS. As discussed earlier, dilution is necessary to reduce the viscosity of the SLDM mixture and reduce the hindrance (Zimmels, 1984).

In combination, or just after the addition of dilution water, the manure slurry is agitated to wash sand grains free of manure. In mechanical systems, agitation is achieved by the turbulent addition of dilution water near the base of the separation unit and by the sand removal auger. Passive systems achieve agitation by the flush conveyance system. Sedimentation, the third step, results from a quiescent condition or the application of centrifugal force. In both mechanical and passive separation devices, sedimentation occurs by differential settling, where the settling velocity of the sand grain is greater than that of manure particles (Kim and Stolzenbach, 2003). Passive settling devices also have a horizontal component to the flow velocity, causing saltation of settled particles. Saltation is the movement of particles by bouncing along the channel bottom, occurs when the incomplete scour velocity has been achieved (Liu, 2001). Sand removal, the final step, is the mining of separated sand from the separation devices.

A benefit of mechanical SSS is that all four critical steps in the sand removal process are package in a single machine. Mechanical SSS can operate with any manure conveyance system. Passive SSS require that dilution and agitation occur in part of the manure conveyance system. Sand removal in passive systems is a manual process requiring excavation using a front-end loader and operator.

2.4 Sand separation technologies

Dairy producers interested in separating sand from manure have several technologies to select from depending on their goals for separation and conveyance system employed at the dairy farm. First SLDM is collected using either a scrape or flush system. There after the SLDM must be conveyed to a central treatment location, typically using mechanical or hydraulic conveyance. Sand removal is achieved by either a mechanical or passive separation unit. Then the sand is moved into storage and the liquid slurry travels to the next treatment step in the manure management system. Each step is described in detail below.

2.4.1 SLDM collection and conveyance

Two types of manure conveyance exist for dairy farms, mechanical and hydraulic (Kirk, 2005). Mechanical conveyance includes both scrape and vacuum-scrape, while hydraulic systems are categorized as scrape-flush and flush (Kirk, 2005).

Scrape and vacuum-scrape system use a device to push manure from the freestall alley to a collection/treatment point near the building. Included are traditional alley scrapers, tire scrapers mounted on skid loaders, and the vacuum-scrapers (vacuum-scrape). Vacuum-scrapers use a scraper bar to collect the manure which is transferred into a self-propelled or trailer mounted tank using vacuum (similar to a vacuum cleaner), allowing it to be transported to the SSS. The product of these systems are manure as excreted mixed with bedding and urine.

Flush collection systems create a wave of water that collects manure from the freestall alley and moves it to the point of treatment. A water release rate of at least 0.63 m^3/s is recommended for SLDM (Harner et al., 2003). Scrape-flush systems combine physical scrape collection of manure from the freestall alleys with hydraulic conveyance of manure from the barn. Manure collection by the scraper is deposited into a flush channel that conveys manure from the barn. Hydraulic collection and conveyance systems are typically designed to meet or exceed the mean scour velocity of the largest particle, generally in the range of 2.4 to 3 m/s for SLDM (Harner et al., 2003). Wedel (2000) suggested that the mean flow velocity should be between 1.5 to 2.5 m/s. This flow velocity range achieves the initiation scour velocity for the typical distribution of sand particles used for bedding. Achieving the complete scour velocity is desirable because it assures that particles will not settle in the conveyance system.

2.4.2 Mechanical sand separation systems

Counter-current upflow separators (CCUS) and centrifugal separators [hydrocyclones (HC)] are the two mechanical SSS technologies. Each is discussed below.

2.4.2.1 Counter-current upflow separators

Counter-current upflow separators combine the four key steps of sand separation into a compact continuous flow machine. Concepts used in sedimentation basins, aerated grit chambers, and hydrocyclones are all used (Krou et al., 2006; Wedel and Bickert, 1996). Figure 2.3 shows the configuration of a column style CCUS. The sand manure separator (SMS) employed at GMF and MDF and shown in Figure 2.4 is a commercial version of the CCUS.

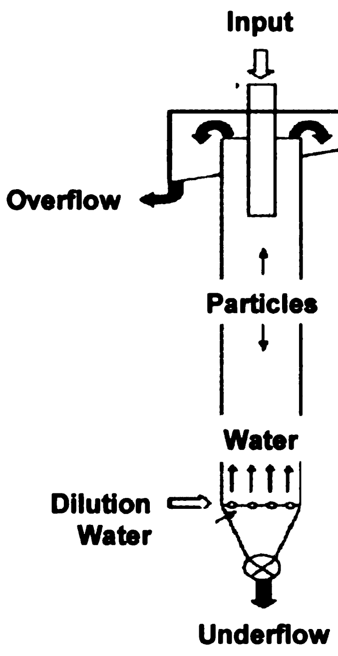

Figure 2.3: Diagram of column style counter-current upflow separator (Kim, 2003)

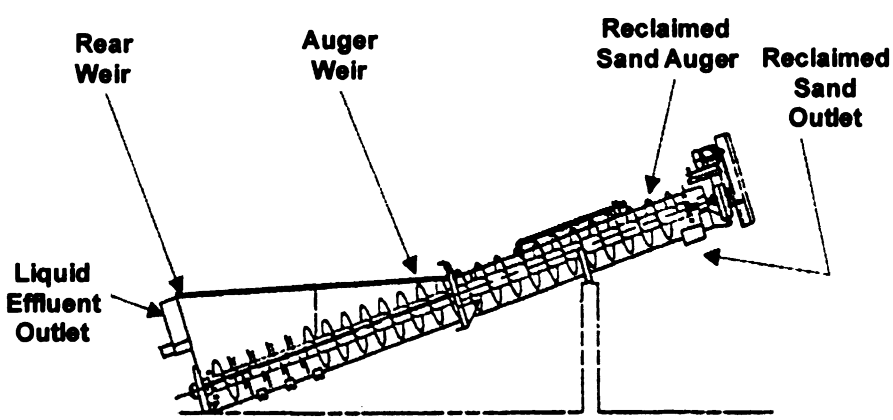

Figure 2.4 McLanahan Sand Manure Separator (Inglis et al., 2006)

Counter-current upflow separators use a pool of fresh or recycled water to dilute the SLDM input. Pool depth is determined by an overflow weir that is set based on the input rate of dilution water and SLDM, generally specified by the manufacturer. Dilution water is injected into all variations of the CCUS so that it creates a rising current. SLDM is metered into the unit at a point near the surface of the pool of dilution water. The difference in the elevation of the inputs (dilution water and SLDM) results in the counter-current effect of settling sand and a rising current of dilution water.

Figure 2.2 shows the forces exerted on a sand particle in the pool of a CCUS. Under ideal conditions, the buoyant and drag forces are less than the weight force for the smallest sand particle to be separated, but greater than the gravity force for organic particles. Otherwise, settling will not occur and the sand particle will be carried out of the CCUS with the overflow fluid. Due to the particle size, fine sand, silt and clay are often washed out of the CCUS with organic matter (Tables 2.5 and 2.6). The proportionally large surface area of the small particles increases the drag force exerted on the grains. The opposite condition, insufficient buoyant and drag forces, will result in sand and organic particles settling together.

Counter-current upflow separators operate with the four major types of SLDM conveyance and capable of achieving Goals #1 and #2 (discussed in Section 2.3.4). In most cases, CCUS require a secondary removal step to achieve Goal #3, sand-free manure.

2.4.2.2 Centrifugal separations

Centrifugal separators, or hydrocyclones (HC), separate solid material from slurries by centrifugal sedimentation. Hydrocyclones operate on the theory that suspended particles subject to centrifugal acceleration force denser particles to the cyclone wall where they settle by gravity (Svarovsky, 1990). Classification of sand in the mining industry is a common application of HC technology.

Hydrocyclones consist of a cylindrical body and a cone section, as shown in Figure 2.5. The cylinder section includes the inlet, which introduces flow to enter tangentially. Tangential entry creates a swirling action inside the cylinder. The swirling action continues and the velocity increases as the slurry moves down the cone section, shown in Figure 2.6. Dense, coarse material exits the cone section through the concentrated suspension outlet, also known as underflow. Liquid is siphoned up the center of the cone and cylinder, exiting the HC through the diluted suspension outlet, commonly referred to as the vortex finder or overflow.

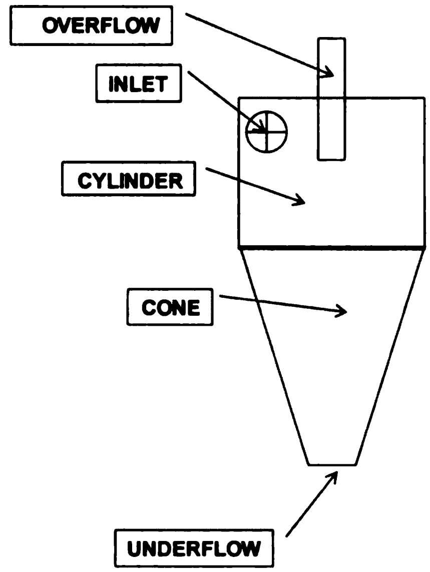

Figure 2.5: Typical centrifugal separator cross-section

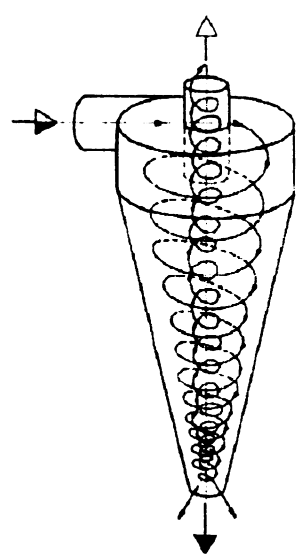

Figure 2.6: Hydrocyclone flow pattern (Metcalf and Eddy, 1991)

To initiate the swirling flow pattern in the HC, the inlet is connected at a right angle to the cylinder. Liquid manure is pumped into the HC inlet. As the fluid is accelerated inside the cyclone, particles are subjected to three forces: external and internal acceleration and drag, due to flow (Svarovsky, 1990), Figure 2.7. The effect of gravity in HC is generally neglected. Velocity is greatest near the center of the HC, below the overflow, and decreases proportionally as the radius increases until the cone radius is less than the overflow radius. When the overflow radius exceeds the cone radius, a siphon is created at the core drawing liquid and fine solids out the overflow.

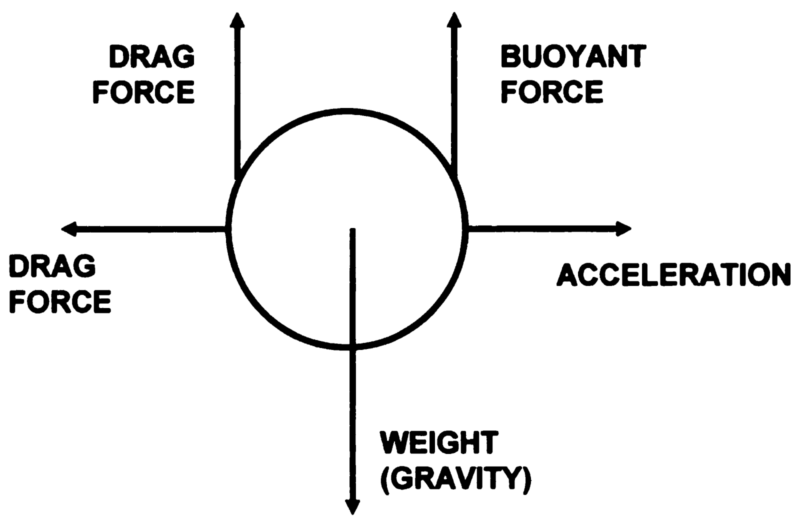

Figure 2.7: Force balance about a particle settling in a centrifugal separator

Flow velocity in the HC can be resolved to three components: axial, tangential and radial (Svarovsky, 1990). Axial velocity results in the downward flow along the outer wall of HC and an upward flow near the core of the cyclone. Because of axial flow, HC are created with an underflow orifice pointed downward. Sand moving downward is collected near the bottom and discharge through the underflow at the bottom of the cone. The tangential velocity is responsible for the movement of dense particles to the cylinder and cone walls. Radial velocity, the weakest velocity component, occurs near the outer wall of the HC and is directed inward, its magnitude decreases with decreasing radius.

The necessity of the pump to initiate flow and create pressure in the HC limits the applicability. Hydrocyclones can achieve goals 1 and 2 for sand separation. However, due to the influent pump are most often used as a second level of sand separation to achieve sand-free manure, goal 3.

2.4.3 Passive sand separation systems

Passive gravity separators (PGS) are adapted from grit (type) sedimentation tank design used in municipal and industrial wastewater treatment (Wedel, 1995). These systems operate in the realm of discrete settling where particles settle individually with minimal interaction with other particles (Metcalf and Eddy, 1991).

Early PGS systems used in municipal wastewater treatment were designed to remove a specific percentage of grit based on the tank overflow rate based on isoremoval plots (Swamee and Tyagi, 1996 ; Jin, et al., 2000). The discrete settling conditions typically modeled in wastewater treatment are caused by low total solids concentration (TS). Common PGS used to for separating sand from dairy manure include the settling basin and sand lane. Figure 2.8 shows the basic layout of a PGS used to settle sand from manure.

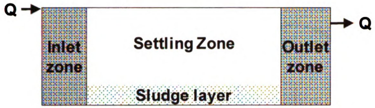

Figure 2.8: Typical settling basin configuration

Q = flow rate, m^3/s

Passive gravity separators are generally coupled with a hydraulic conveyance system (Fulhage, 2003). Hydraulic (flush) conveyance creates a condition similar to grit sedimentation tanks by using large quantities of dilution water.

The success of PGS depends on the ability to slow the fluid velocity to between 0.3 to 0.6 m/s (Harner et al., 2003). According to Shields' equation (Equation 2.4), that velocity range will allow settling of some sand particles, but some particles with a diameter of 2.3 mm or less may pass through the system. In theory, manure particles will remain suspended in that velocity range.

Forces exerted on a particle in a PGS include both vertical and horizontal. Vertical forces are buoyant, drag, and weight, similar to the CCUS. The difference in the vertical force of the PGS, compared with the CCUS is the magnitude of the buoyant forces, as there is no rising current. Two horizontal forces are exerted in a PGS, flow (momentum) and drag (friction), Figure 2.9. The flow force is created by the momentum of hydraulic conveyance system.

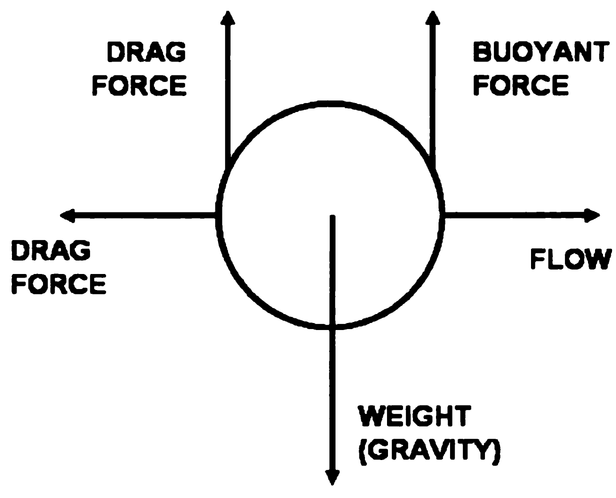

Figure 2.9: Force balance about a particle settling in a passive gravity separator

Settling basins are relatively deep storages where settled material accumulates for long periods (weeks to months). In agriculture, settling basins are designed to accumulate solids to a predetermined level. The time required to reach that level is the accumulation period. To dissipate the hydraulic conveyance energy, settling basins operate full of fluid. The sudden decrease in velocity of the flush water allows material entering the settling basin to settle by gravity. Gravity settling, as discussed in Section 2.3.5, is influenced by particle size and density. Because sand and manure solids accumulate over time in a settling basin, sand removed is generally not clean enough for reuse as bedding. Settling basins are designed based on the settling velocity of the smallest particle to be separated (Wedel and Bickert, 1996). Using the settling velocity (Equation 2.3) and flow rate of the conveyance system, the surface area of a settling basin is determined using Equations 2.8.

$$A = \frac{Q}{V_S} \tag{2.8}$$

A = plan view area of basin, m^2

Flow rate of the conveyance system is used because that is assumed to be the settling basin inlet flow rate. The depth of the settling basin can then be determined using the conveyance flow rate, basin width and scour velocity in Equation 2.9.

$$D = \frac{Q}{V_H * W} \tag{2.9}$$

D = chamber depth, m

W = basin width, m

Fulhage (2003) reported that settled solids accumulated at a rate of 0.06 to 0.07 m^3/cow/d. Sand accounts for approximately for a quarter of the accumulation or 0.016 m^3/cow/d.

Sand lanes were developed to separate sand of sufficient quality for reuse while removing enough sand to minimize downstream problems. Unlike settling basins, sand lanes are shallow and drain completely between manure flushes. The design of sand lanes is such that the flow from the conveyance device is dissipated quickly, creating a shallow even flow over the entire width of the lane. Settling and scour velocities, Equations 2.3 and 2.7, of the largest particle size to be removed should serve as the design parameters for controlling flow rate in the PGS (Harner et al., 2003). Equations 2.8 and 2.9 are used to determine the dimensions (Wedel and Bickert, 1996). Sand lanes are sometimes constructed with a gradual slope to facilitate drainage. Sand is removed from PGS manually using a loader. Dilution water volume and sand excavation vary from farm to farm depending on management.

2.4.4 Integration of technologies to create a sand separation system

Determining the goals of sand separation (Section 2.3.4) and the preferred manner for manure collection and conveyance (Section 2.4.1) limit sand separation options. Similarly, not all sand separation technologies can achieve each goal for sand separation. Figure 2.10 is a simple decision flow diagram of conveyance options with sand removal technologies and sand separation goals.

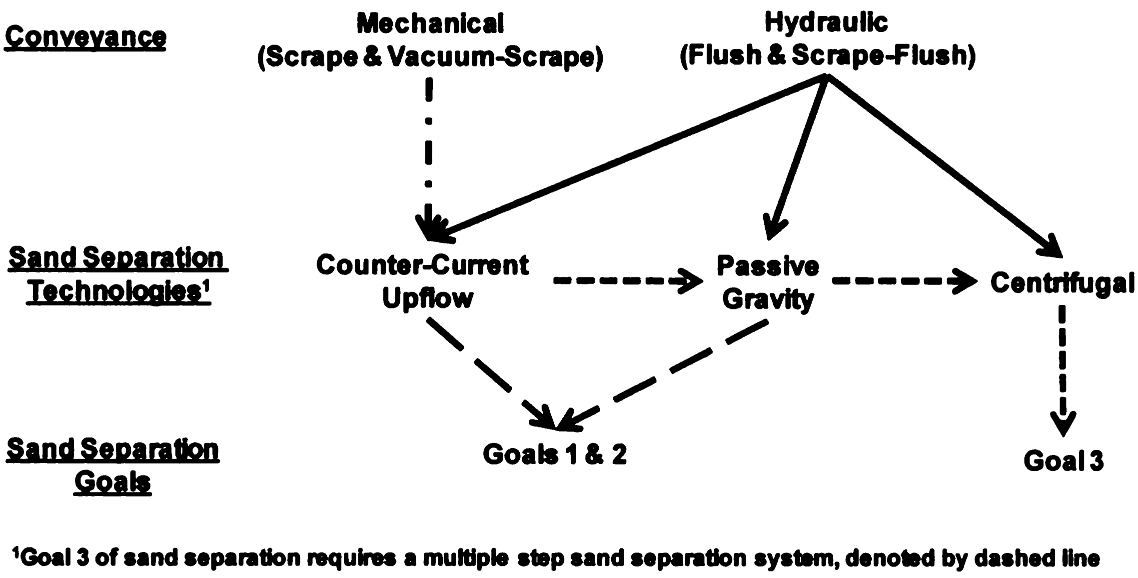

Figure 2.10: Integration of conveyance and sand separation technologies

Both CCUS and PSG can achieve goals 1 and 2 with a single treatment unit or level. To achieve sand separation goal 3, sand-free manure, multiple sand separation technologies are generally integrated in series into a system, similar to the multi-level system at GMF. Multiple technologies increase the range of sand particle which can be effectively removed, compared to an individual separation unit.

Compared to dairy farms using organic bedding, sand bedded dairy farms require several additional pretreatment steps to remove sufficient sand such that downstream processes, anaerobic digestion, are not negatively impacted (goal 3). As discussed previously, manure with organic bedding requires little to no pretreatment. For organically bedded dairy farms using AD, pump conveyance is the simplest pretreatment or pre AD management system. In comparison, sand bedded dairy farms require a minimum of two level of sand separation to ensure that sedimentation will not negatively impact AD performance. Short-term storage and pumping equipment are typically associated with each level of the SSS, providing opportunities for changes in the manure characteristics due to aging and aeration.

2.5 Determination of separation efficiency

Sand separation efficiency is the quantitative technique used to determine the effectiveness of the SSS. Mass balance techniques are used to achieve the first research objective, determination of sand removal efficiency by the SSS. Svarovsky (1990) shows the mass balance of solid liquid separation device by Figure 2.11.

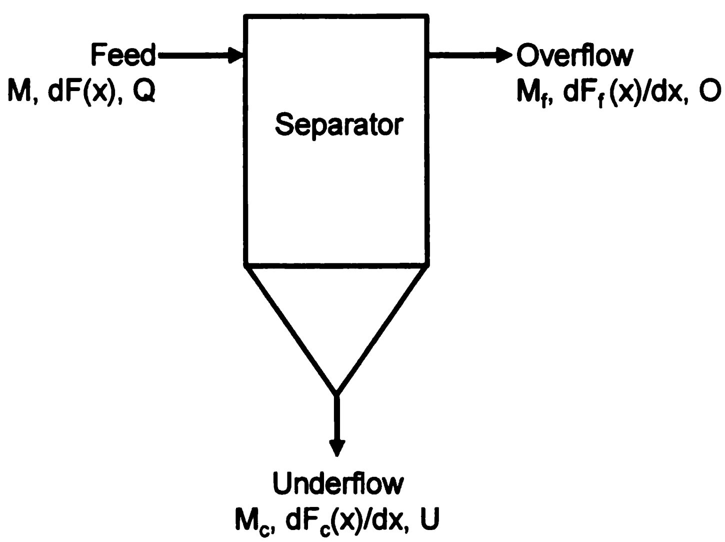

Figure 2.11: Schematic diagram of a separator (Svarovsky, 1990)

M = mass of particles contained in the influent

M_c = mass of the coarse particles contained in the underflow

M_f = mass of the fine particles contained in the overflow

dF(x) = mass flow of the influent

$dF_f(x)/dx$ = mass flow of the fine effluent

$dF_c(x)/dx$ = mass flow of the coarse effluent

Q = influent flow rate

O = overflow flow rate

U = underflow flow rate

Assuming that material does not accumulate in a separation device, the mass of the sand contained in the influent must equal the total mass of the sand contained in the system products, overflow and underflow (Svarovsky, 1990). The governing mass balance equation is shown as Equation 2.10.

$$M = M_c + M_f \tag{2.10}$$

Overall separation efficiency is described as the ratio of the mass of coarse particles removed to the mass of the feed in Equation 2.11.

$$E_T = \frac{M_c}{M} * 100 \tag{2.11}$$

E_T = overall separation efficiency, %

The overall separation efficiency can also be calculated using the mass flow of the fine particles contained in the effluent as shown in Equation 2.12.

$$E_T = 1 - \frac{M_f}{M} * 100 \qquad \textbf{(2.12)}$$

Mass balance closure is the comparison of the mass of the influent material to the mass of the effluent of a system or unit. Manure and sand in theory do not accumulate in SSS operating at equilibrium. Ideally the mass of influents and effluents would sum to 100%, however do to the dynamic operation of commercial SSS closures to within ±10%systems were deemed acceptable. Percent difference, the technique identified by Gooch (2007) for determining the accuracy of mass balance closure, is shown in Equation 2.11 (Gooch, 2007).

$$PD = \left(\frac{\Sigma_{influents} - \Sigma_{effluents}}{\Sigma_{\mathrm{influents}}}\right) * 100 \qquad \textbf{(2.13)}$$

PD = Percent difference

$\Sigma_{\mathrm{influents}}$ = sum of all material entering the device

$\Sigma_{\mathrm{effluents}}$ = sum of all the material entering the device

2.6 Anaerobic digestion

Anaerobic digestion is the biological conversion or degradation of biomass into biogas and digestate (slurry exiting the digester). Digestion technology, an advance treatment technology used around the world, has been in use on livestock farms in the United States for over thirty-five years. The first known farm application was on a swine farm in Iowa in 1972 (Lusk, 1995).

During anaerobic digestion, carbon based material (biomass) is degraded biologically in an atmosphere devoid of oxygen (Bracmort, et al., 2008) by multiple microbial communities in a symbiotic relationship. Included are the acid forming (hydrolytic, fermentatative, acidogenic) and methane-forming (methanogenic) (Rozdilsky, 1997) microorganisms. Figure 2.12 shows the multiple step process and products.

Organic Matter $\xrightarrow[\text{Bacteria}]{\text{Acid-Forming}}$ **Simple Organic Acids** $\xrightarrow[\text{Bacteria}]{\text{Methane-Forming}}$ **Biogas**

Carbohydrates	Acetic	Methane
Proteins	Propionic	Carbon Dioxide
Fats	Butyric	Water Vapor
	Formic	Ammonia
		Hydrogen Sulfide

Figure 2.12: Biology of anaerobic digestion (Barker, 2001)

Biogas, considered a low-grade form of natural gas, is a mixture of methane (CH_4), carbon dioxide (CO_2) and other trace gases including hydrogen sulfide (H_2S). The energy density of biogas ranges from 16,750 to 23,450 kJ/m^3 (MWPS, 2000). Digestate, AD effluent, is a mixture of undigested and partially digested biomass and water.

Anaerobic digestion is beneficial to livestock producers for numerous reasons including the stabilization of waste, reduced odor and pathogens, decreased emissions and the production of renewable energy (Wright et al., 2003; U.S Environmental Protection Agency, 2002). Wright et al. (2003) reported a 3-log reduction in fecal coliform due to anaerobic digestion.

There are several common designs of anaerobic digesters including covered lagoons, plug flow, complete mixed and fixed film (Wilkie, 2005). The digester design for an individual farm is dependent on the solids concentration of the slurry, space constraints and the farm management preference. Figure 2.13 is a decision support aid to identify appropriate conditions for anaerobic digestion.

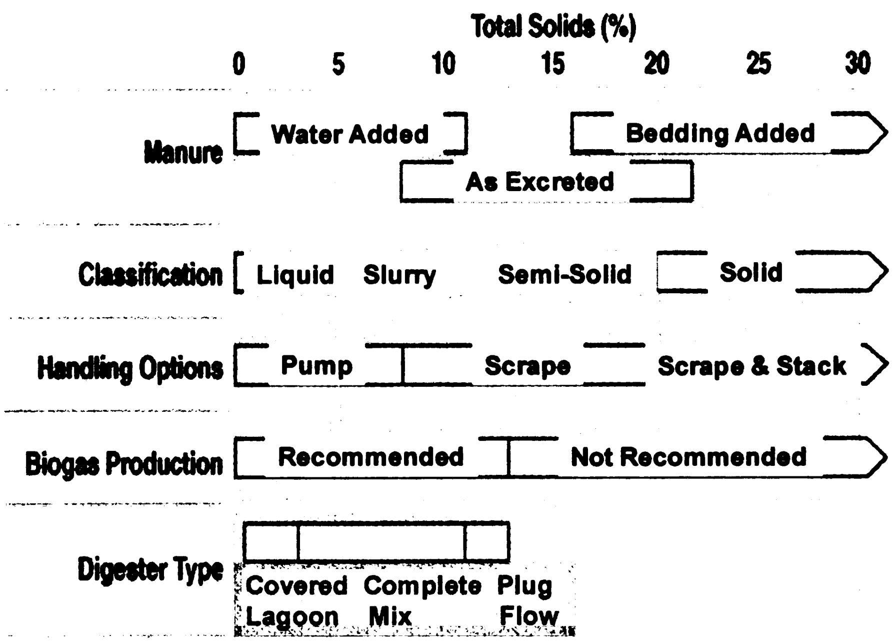

Figure 2.13: Appropriate manure characteristics for anaerobic digestion (U.S. Environmental Protection Agency, 2002)

2.6.1 Biogas potential of dairy manure

Prediction of biogas production from AD systems is normally based on the VS mass or the chemical oxygen demand of an organic material. Before estimating biogas production, it is important to consider the digestibility of the biomass. One method to determine the potential to produce biogas, anaerobic digestibility, is the biochemical methane potential test, also known as serum bottles (Chynoweth et al., 1993; Owen et al., 1979). Serum bottle tests identify unexpected results associated with site-specific constituents. Serum bottles use relatively small quantities of sample, less than 250 ml, to predict anaerobic digestibility and total biogas potential (Owen, et al., 1979). Using serum bottle techniques, for manure, biogas production, has been reported to be in the range of 0.18 and 0.39 m^3/kg of VS destroyed (U.S. Department of Agriculture, 2007; Steffen et al., 1998; Morris, 1979). To address concerns with sample size and data collection, anaerobic respirometer techniques have been developed which use large samples sizes and automated gas measurement (Szczegielniak, 2008). However, sources of variability during the laboratory prediction of biogas potential still occur, due to a number of factors including nutrient limitation, bacterial acclimation, feedstock characteristics (VS) and experimental or sampling error.

While the biogas production determined during the BMP does give an indication of the biogas potential, it is not intended to be used for design and equipment selection. It is recommend that pilot-scale test or actual operational data be determined prior to the sizing and selection of biogas utilization equipment. Using the range of predicted biogas production values, the biogas yield from a commercial system can be predicted using equation 2.14 (U.S. Department of Agriculture, 2007).

$$Biogas = VS * VS_{Converion} * MC * BP \qquad \textbf{(2.14)}$$

Biogas = volume of biogas produced, m^3

VS = mass of volatile solids, kg

$VS_{Conversion}$ = volatile solids destroyed in AD, %

MC = manure collected, %

BP = biogas potential, m^3/kg of VS destroyed

According to U.S. Department of Agriculture (2007), AD systems are expected to produce 1.9 m^3 of biogas/cow/d. Energy potential can be determined once the biogas production is known using equation 2.15.

$$Energy\ Potential = Biogas * Energy\ Density \qquad \textbf{(2.15)}$$

Energy Potential = theoretical energy available, kJ

Energy Density = 16,750 to 23,450 kJ/m^3

The energy potential can be converted to the theoretical electrical energy output using the conversions factor of 3,600 kJ per kilowatt-hour (Glover, 1995). According to U.S. Department of Agriculture (2007), using the basic stoichiometric calculation for chemical oxygen demand (COD), the manure from a single cow can generate approximately 42,000 kJ/d or 11.6 kWh/d. Stoichiometrically, for every kilogram of COD destroyed, 0.395 cubic meters of methane are produced (Speece, 1996). Wright et al. (2003) provided a general prediction that seven mature dairy cows are required to support one kilowatt of generation capacity. However, actual biogas yield will vary based on a number of site-specific influences including feedstock, management, toxic substances and system design.

Operating data from existing AD indicates a significant amount of variability in the installed electrical generation capacity. Table 2.7 summarizes the key operational data from a majority of the operating AD in the United States, compiled by the United States Environmental Protection Agency (2009).

Table 2.7: U.S. Farm Based Anaerobic Digester and Electrical Generation Capacity

Anaerobic Digester Type	Total Number of Systems	Mean Number of Animals	Installed Generation Capacity			
			Number of Systems	Mean		Standard Deviation
				(kW)	(animals/kW)	(animals/kW)
Complete Mix	26	1,628	22	415	4.7	2.6
Covered Lagoon	10	1,778	8	247	9.2	6.3
Fixed Film	1	250	1	30	8.3	
Horizontal Plug Flow	32	1,621	30	330	7.2	3.8
Induced Blanket Reactor	2	775	2	100	7.5	
Mixed Plug Flow	33	2,878	27	589	4.2	1.1

Table F.1 in Appendix G, evaluates the performance of AD, including the bedding material and feedstocks. Similar to laboratory data, field data also indicated that biogas production and the subsequent utilization was highly variable, often with the standard deviation exceeding 50% of the mean for installed generation capacity per animal. The variability of biogas data available from both laboratory experiments and operating commercial systems indicated how important it is that system planners understand site-specific characteristics to deal with uncertainty during the design of the biogas utilization system.

2.6.2 Mixing

Mixing in an AD is important for introducing new substrate to the viable bacterial populations, heat transfer, reducing particle size and for releasing biogas from the slurry (Karim et al., 2005a). For digester using SSS effluent, mixing is also needed to minimize the settling of residual sand in the digester tanks.

Mixing options for anaerobic digesters included mechanical mixers, slurry recirculation or biogas recirculation (Karim et al., 2005a). Mechanical mixers have been identified as being the most efficient, however servicing of internal mechanical mixing systems in closed digester vessels is problematic (Brade and Noone, 1981). Slurry and biogas recirculation mixing uses external components to recycle material for mixing, simplifying maintenance and operation. Several resources have identified recirculation as the most efficient mode of mixing AD (Karim, et al., 2005a). Design of a mixing system should maximize biogas production while minimize the parasitic energy load of the mixing system and grit accumulation. The mixing pattern, intensity and duration are believed to impact biogas production but the body of literature is contradictory (Karim et al. 2005b).

Traditionally, acceleration, force and power equations have been used to determine the bulk mixing energy requirements of anaerobic digesters (Smith, 2008). If the mixing time and scour velocity of the particle of interest are known, Newton's Second Law can be applied to determine the required acceleration, Equation 2.16.

$$Acc = V_H * t \tag{2.16}$$

Acc = acceleration, m/s^2

t = time, s

ac

F

m

On

de

Using Equation 2.16 to determine the acceleration, the required force to achieve the acceleration can be determined by Equation 2.17.

$$F = Acc * m \tag{2.17}$$

F = force, N

m = mass of the material being accelerated, kg

Once the force is known, the mixer power required to achieve the force is determined by Equation 2.18.

$$P = F * V_H \tag{2.18}$$

P = power, kW

In recent years, computational fluid dynamics (CFD) software has been used to improve mixing systems design, predict the overall flow pattern, location of circulation cells and stagnant regions, trends of liquid velocity profiles and volume of dead zones (Vesvikar and Al-Dahhan, 2004). Dead zones are defined as an area where the velocity was less than 5% of the maximum tank velocity (Wu and Chen 2007) and can reduce the effective volume of a digester tank by 70% (Wu and Chen, 2007). The 3-Dimensional Multiphase CFD model prepared by Vesvikar and Al-Dahhan (2005) indicated that the volume of dead zones in typical an AD ranged from 11% to 60%, depending on mixer and tank configuration. For their research, dead zones were defined as having a fluid velocity less than 5% of the maximum, 17-27 cm/s. Wu and Chen (2007) found that increasing viscosity (total solids concentration) decreased high velocity zones while having little impact on the percentage of low velocity zones that lead to dead zones.

Even with improved modeling techniques, the only firm recommendation concerning the power input for anaerobic digester agitation was made in an EPA manual published in 1979. The U.S. Environmental Protection Agency (1979) manual suggested a mixing power input n the range of 5.3 to 7.9 kW/1000 m^3 for anaerobic digester tanks.

Karim et al. (2005a) tested six biogas recirculation mixing regimes, which the varied the recirculation rate from 0 to 3 L/min and the draft tube height from the tank bottom from 13 to 40 mm. No significant difference in biogas production was identified. The low solids content of the substrate and the long retention time in the AD were cited as causes for results. In a follow up study, Karim et al. (2005b) confirmed that mixing did not improve gas production for dilute feedstocks (<5% TS). However, increasing the feedstock TS concentration to 10% did produce differences in biogas production based on mixing and mixer type. Biogas production improved by 15% to 29% for mixed digester with high solids compared to unmixed conditions (Karim et al., 2005b). Hoffman, et al. (2008) found that mixing intensity had no impact on biogas production, while operating four continuously stirred digester with mixing intensity ranging from 50 to 1,500 revolutions per minute. The contradictory data on mixing and biogas production demonstrates how much uncertainty exists regarding AD mixing and the impact of performance.

2.6.3 Heating requirements

Anaerobic digesters typically operate in one of two temperature ranges, mesophilic (35°C to 41°C) or thermophilic (52°C to 57°C) (Pennsylvania State University, 2009). The elevated operating temperature is intended provide the optimum environment for the microbial consortium responsible for the anaerobic degradation. Dilution water added to the manure stream during SSS influences the design of the heating system. Additional mass of dilution water increases the energy needed to achieve the target operating temperature of a digester (Inglis, 2006). The formula for used to determine the heat requirement of digester influent is Equation 2.19.

$$H = C_{p,w} * M_w * \Delta T \qquad \textbf{(2.19)}$$

H = total heat, kJ

$\mathbf{C_{p,w}}$ = specific heat of water

$\mathbf{M_w}$ = mass of water, kg

$\mathbf{\Delta T}$ = temperature difference, °C

As shown in Equation 2.20, Equation 2.19 can be expanded by adding terms to account for other components in the slurry, such as sand.

$$H = (C_{p,w} * M_w * \Delta T) + (C_{p,s} * M_s * \Delta T) \qquad \textbf{(2.20)}$$

$C_{p,s}$ = specific heat of sand

M_s = mass of sand, kg

The specific heat of water and sand is 4.18 kJ/kg °C and 0.76 kJ/kg °C, respectively (Inglis, Gooch and Timmons, 2006).

2.6.4 Sand bedding and anaerobic digestion

Currently, there are only three anaerobic digesters operating on sand bedded dairy farms. Green Meadow Farms (GMF) near Elsie, MI operates complete mixed anaerobic digester with SSS effluent serving as the feedstock. The other systems are at the Fair Oaks Dairy, near Fair Oaks, IN and Bridgewater Dairy near Bridgewater, OH. Anaerobic digestion technology has not been more widely deployed on dairy farms using sand bedding due to the history of system failures caused by grit accumulation and clogging (Rozdilsky, 1997; Wilkie, 2005; U.S. Department of Agriculture, 2007). A lack of data on the efficiency of SSS has fueled a debate on the cost/benefits of AD use on dairy farms using sand bedding (Gooch and Inglis, 2007; Inglis, 2006). Important issues include the possibility of sand settling and rapidly filling tanks, excessive wear and tear of equipment and reduced energy production due to the need to heat the dilution water required to remove sand from the manure, as discussed in the subsections below.

CHAPTER 3: EXPERIMENTAL METHODS

This Chapter summarizes the methods and procedures used to conduct the research associated with the objectives outlined in Chapter 1.

3.1 Solids Analysis and characterization procedures

Table 3.1 summarizes the standard procedures used for the characterization of TS, FS, VS and PSD of sand and manure samples with the following modification. Weights were taken on a "hot basis" instead of "cold basis." To measure on a "hot basis," weights were taken immediately after removing the sample from the oven at 105°C; this technique was preferable because of the elimination of the potential for a faulty desiccant allowing moisture to accumulate and alter weights (Wedel, 1995).

Total solids are the sum of dissolved and insoluble organic and inorganic solids contained in the sample. Percent total solids was defined as the ratio of the mass of the dried sample to the mass of the original (wet) sample and was calculated using Equation 3.1.

$$TS = \frac{m_{dry}}{m_{sample}} * 100 \qquad (3.1)$$

TS = total solids, %

m_{dry} = sample mass after drying, g

m_{sample} = initial (wet) sample mass, g

The ash remaining after ignition of the sample constituted the FS, or inorganic material, Equation 3.2 was used to calculate the percent FS. Fixed solids are the dissolved and insoluble inorganic material remaining after the sample has been combusted at 550°C for at least one hour.

$$FS = \frac{m_{ash}}{m_{dry}} * 100 \quad (3.2)$$

FS = fixed solids, %

m_{ash} = sample mass after igniting, g

The portion of the sample vaporized during ignition is the VS; the percent VS are calculated using Equation 3.3.

$$VS = \frac{m_{dry} - m_{ash}}{m_{dry}} * 100 \quad (3.3)$$

VS = volatile solids, %

The percent total solids are equal to the sum of the fixed solids (FS) and volatile solids (VS), Equation 3.4.

$$TS = VS + FS \tag{3.4}$$

Table 3.1: Standard procedures for manure and sand characterization

Procedure	Abbreviation	Standard	Source
Total solid*	TS	2540-B	APHA, 2008
Fixed solid*	FS	2540-E	APHA, 2008
Volatile solid*	VS	2540-E	APHA, 2008
Particle size distribution	PSD	D422-63	ASTM, 2002
*Modified to use hot weight measurement			

3.2 Particle size distribution

Particle size results are often reported as the percent retained or passing a specified sieve, using Equation 3.5.

$$Percent\ retained = \frac{(M_{sample} - S_{n,acc})}{M_{sample}} \tag{3.5}$$

M_{sample} = mass, hot basis, of the initial sand sample

$S_{n,\,acc}$ = mass of sand sample accumulated on the n^{th} sieve

The percent passing for a given sieve was calculated using Equation 3.6.

$$Percent\ passing = \frac{(M_{sample} - X_{n,acc})}{M_{sample}} \tag{3.6}$$

$X_{n,\,acc}$ = mass of total sand sample accumulated on the sieve of interest and all larger sieves

3.3 Laboratory quality assurance

Samples for TS, FS, VS and PSD were refrigerated at 4 to 6°C until the analysis was conducted and were tested within 48 hours of collection. Duplicate analytical evaluations were conducted on all samples. Similarly, compromised samples were re-tested when additional samples were available. Samples were saved until analysis was completed and a preliminary evaluation of the data performed.

3.4 Statistics analysis

Data generated from research at GMF and MDF was evaluated using descriptive statistical techniques including mean, standard deviation, coefficient of variation, median and count. Coefficient of variation was used to compare the variability of data collected at different sample locations. Count refers to the number of samples included in the data set. Data analysis tools in Microsoft Excel were used to conduct the descriptive statistical analysis.

Total and volatile solids data from GMF was also evaluated to determine if the management (Farm 2 or Farm 3), treatment level (SMS, MINI or HC) or the machine (SMS 1-6 and MINI 1-6) contributed to the difference in FS and VS results. The management effect consider differences caused by management style, Farm 2 is operated as a production facility while Farm 3 management is focused on treatment and special needs. Treatment evaluated the changes caused by the different levels of the SSS, while machine considered differences in the data attributed to the six different SMS and MINI that make of the SSS. Data for the different sample locations (feces, SLDM, SMS and MINI); was evaluated as individual samples for significant changes in the FS and VS mass due to management, treatment level and machine differences. To evaluate the impact of the HC on FS and VS, the data from the six different machines at the MINI level was combined for each sample event or day. Similar to evaluation for the individual sample locations, the combined data was also evaluated to identify significant changes in the FS and VS mass caused by management, treatment level and machine. SAS 9.2 was used to perform the analysis of the statistical significance FS and VS data from GMF.

To statistically evaluate the data, normality was first determined. Data that was not normally distributed was transformed to fit into a normal distribution. A generalized linear mixed model (GLMM) in PROC GLIMMIX (SAS Inc., 2006) was used to evaluate the normally distributed data. The mixed model contained both fixed and random effects. Fixed effect groups included management and treatment, while the machine was considered a random effect.

Equation 3.7 was the statistical model used to evaluate the individual samples (feces, SLDM, SMS and MINI) using FS and VS data.

$$y = u + mgt + machine(mgt) + trt + trt * mgt + machine * trt + e \quad \textbf{(3.7)}$$

y = response variable

u = overall mean

mgt (management) = fixed factor about the management factor which had two levels (lactating and special needs)

machine (mgt) = random factor about the sample location which had six levels (1–6 shown in Figure 3.1). Management interacted with the machine as machines 1–4 operated at Farm 2 and machines 5–6 operated at Farm 3.

trt (treatment) = fixed factor about the sample identification which had four levels for FS (feces, SLDM, SMS and MINI) and three levels for VS (SLDM, SMS and MINI)

*trt*mgt* = interaction between *trt* and *mgt*

e = residual term

Due to its single input, the HC (average MINI) had only one fixed effect, treatment, modifying equation 3.7. The resulting statistical model is shown in Equation 3.8.

$$y = \mu + trt + e \tag{3.8}$$

trt = fixed factor about the SSS averaged sample identification which has two levels (MINI and HC overflow)

3.5 Research farms

3.5.1 Farm descriptions

Two commercial dairy farms operating similar SSS were used to collect data associated with the research objectives of this project, GMF and MDF.

3.5.1.1 Green Meadow Farms

GMF houses approximately 2,900 lactating and 300 dry cows at two adjacent facilities, Farms 2 and 3. The three level SSS at GMF, installed 1998 to 2001, includes six SMS, each followed by a passive gravity-settling basin (MINI). Four of the SMS are located at Farm 2 and two are located at Farm 3, as shown Figure 3.1. Farm 2 houses only lactating cows while farm 3 maintains a combination of lactating, dry and fresh cows, referred to as special needs animals.

Feces, urine, sand bedding and water from the drinkers is collected from the freestall barns using a skid loader equipped with a tire scraper. The loader deposits SLDM into reception pits located at the end of each barn. Sand laden dairy manure is metered from the reception pit into the adjacent SMS using an auger or positive displacement pump. Effluent recycled from the phosphorus separation system is used for dilution water. Agitation is achieved by injecting compressed air into the dilution water pool near the bases of the SMS and by the turning motion of the sand removal auger (Figure 2.4). Settled sand in the SMS is removed by the internal SMS screw conveyor and discharge on to a concrete stacking pad. Liquid effluent flows by gravity from the separators into the MINI pits adjoining each SMS. Solids accumulated in the MINI's are excavated and land applied daily.

It should be noted that the MINI's are not a common component of the mechanical SSS. The MINI's were included because the system installed at GMF was the first of its kind and a level of uncertainty existed with the level of sand separation efficiency. Installation of the settling basins provided a second level of sand removal. An attempt to remove the MINI's from the SSS in 2007 resulted in a transfer line from Farm 3 to the transfer station becoming clogged. It is believed that the clog occurred because the residual sand in the SMS effluent and the fact that the transfer line is unlevel, allowing settling sand to pool in the low spots. As a result of the failed attempt in 2007, the MINI's remain an integral part of the SSS at GMF.

After the MINI, liquid manure is pumped to tank 2 (Figure 3.1) at the transfer station, it mixes with liquid manure from the other SMS-MINI systems prior to being pumped to the HC (Figures 3.1 and 3.2). Before entering the HC, manure passes through a macerator to reduce all particles to 12.5 mm diameter or smaller. After passing through the HC, this underflow is directed into MINI #5. HC Overflow, sand-free liquid manure, is pumped into the AD. Digester effluent is pumped to the AD equalization tank before being transferred to the phosphorus separation system.

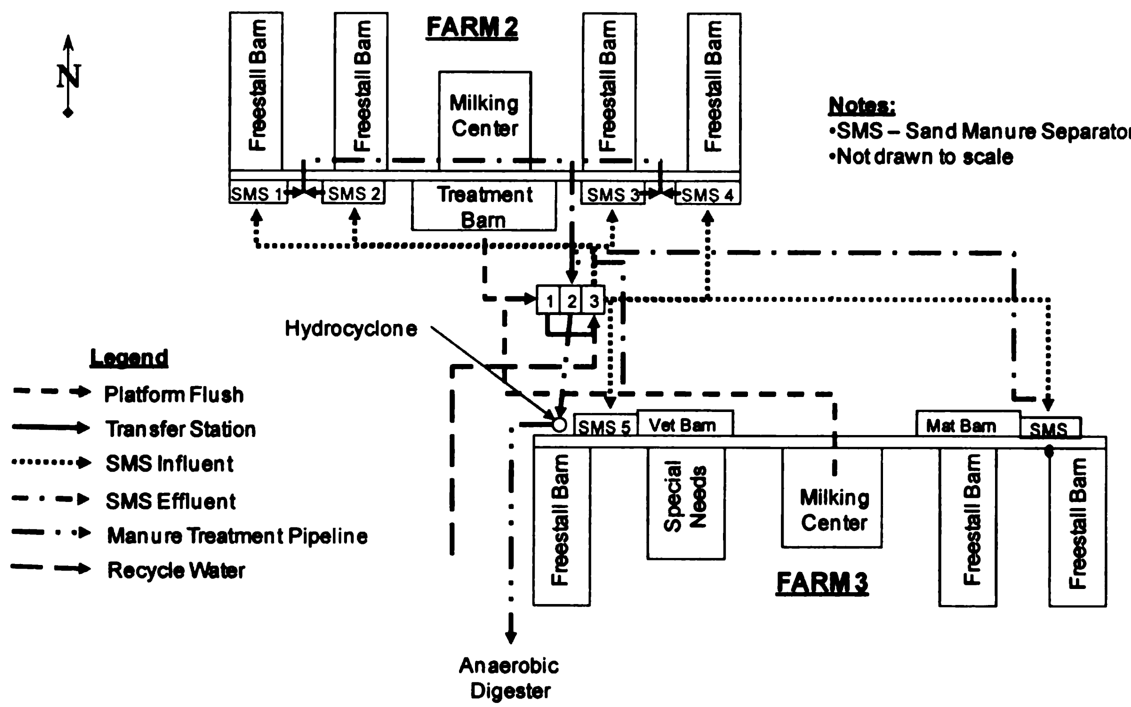

Figure 3.1: GMF SSS schematic

Figure 3.2 shows the general SSS process flow for GMF. Sample points in Figure 3.2 are identified by numbers. The sample numbers in Table 3.2 correspond with Figure 3.2 and offer a description of the sample and collection location.

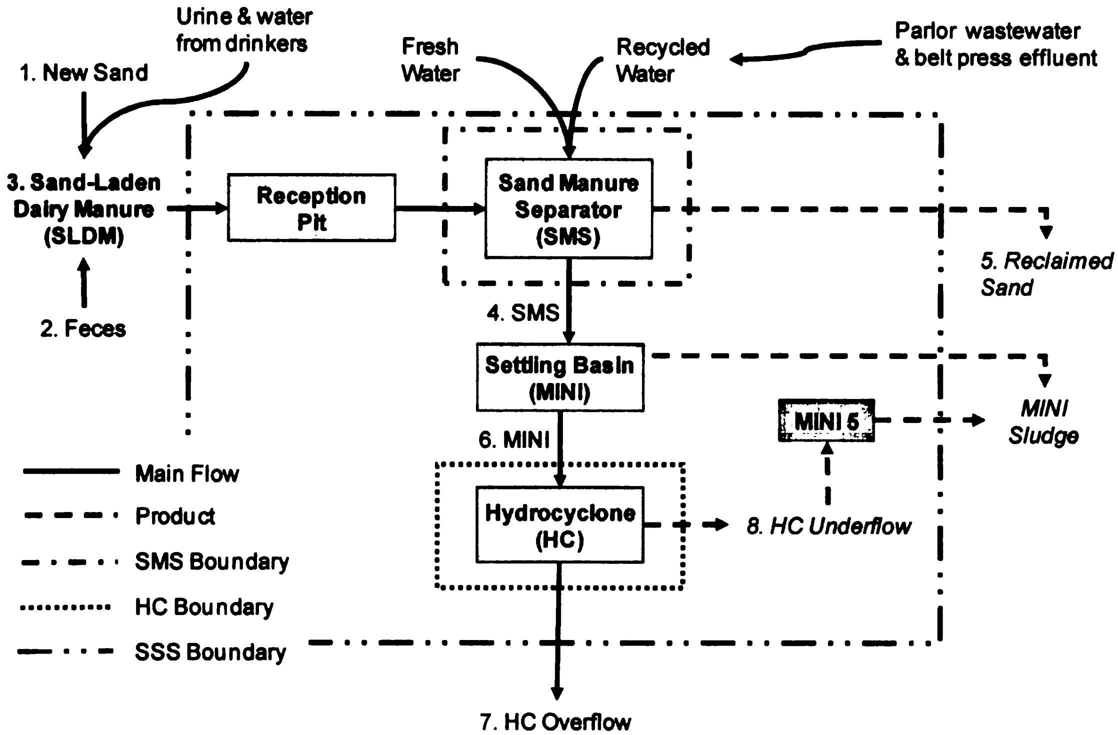

Figure 3.2: SSS process flow diagram – GMF

Table 3.2: SSS sample locations and description – GMF

Sample #	Sample ID	Description	Sample Location
1	New Sand	New bedding sand	Sand stockpile
2	Feces	Feces only	Freestall alley
3	SLDM	Manure, urine, water and sand in a slurry	Metering system discharge
4	SMS	Effluent from SMS	SMS liquid outlet
5	Reclaimed Sand	Reclaimed sand from SMS	SMS sand discharge
6	MINI	Effluent from MINI	MINI overflow effluent
7	HC Overflow	Fine effluent (overflow) from the HC	HC overflow effluent
8	HC Underflow	Coarse effluent (underflow) from the HC	HC underflow effluent

3.5.1.2 Minnis Dairy Farm

MDF houses approximately 600 mature dairy cows. The two-level SSS was installed in 2005 and consists of a SMS and HC, operated in series (Figure 3.3). MDF scrapes manure from the freestall alleys using a skid loader to two reception pits. A piston pump in each reception pit meters manure in to the SMS.

The piston pump operates like a syringe feeding material into the SMS during the down stroke and filling the pump chamber on the up stroke. Milking center wastewater and effluent from the solid-liquid separator are used as dilution water. Effluent from the SMS flows by gravity into a sump from which it is pumped to the HC. Reclaimed sand is removed from the SMS by the built-in screw conveyor. Periodically, the low limit switch is triggered, deactivating the feed pump and consequently, turning off the HC. Overflow from the HC flows into a reception and then pumped to the solid-liquid separator. Hydrocyclone underflow is discharged into the SMS dilution pool. The solid-liquid separator removes coarse manure solids and a portion of the liquid effluent is used as dilution water for the SMS. Excess effluent is transferred to the long-term manure storage. Because this SMS uses a closed-loop configuration, the dilution water has a relatively high solid's concentration and larger ratios, greater than a 1-part SMS to 1-part dilution water, is required. Typically, the SSS at MDF operates for eight to twelve hours each day. Table 3.3 summarizes the sample collection location and description; the numbers correspond with those shown in Figure 3.3.

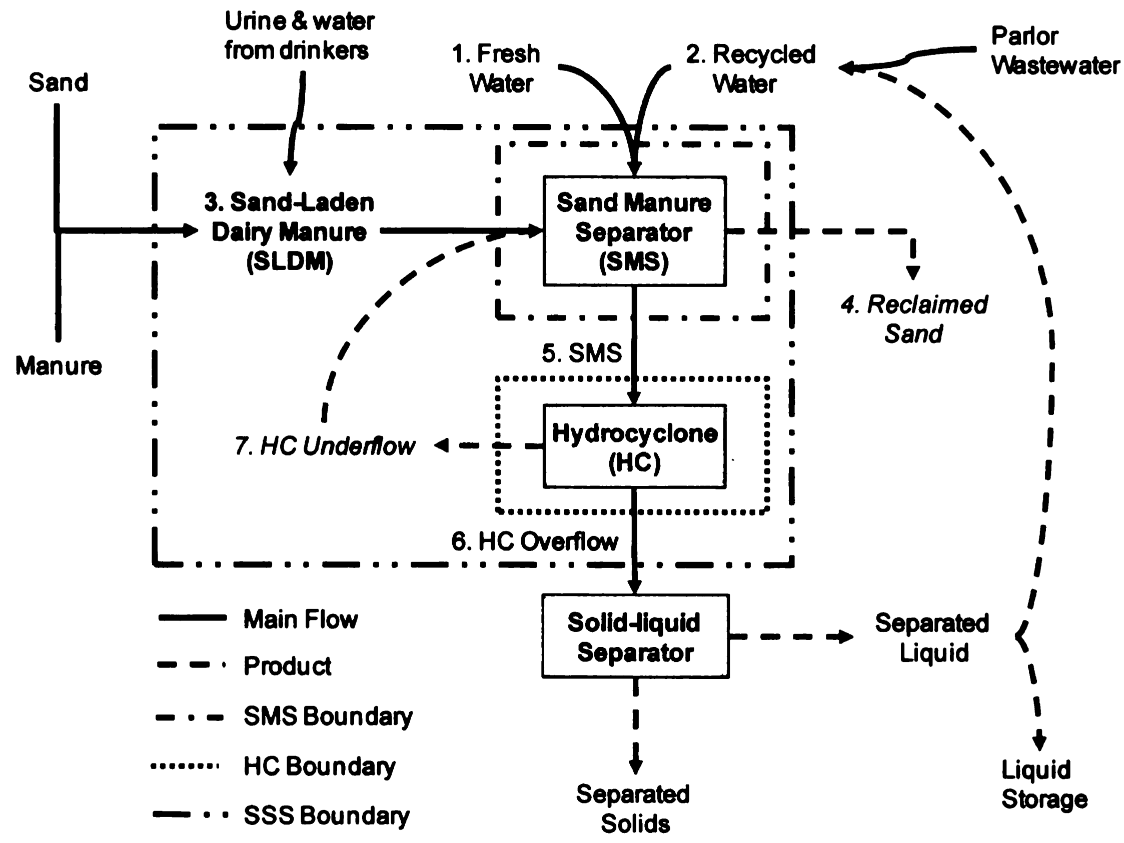

Figure 3.3 SSS process flow diagram – MDF

Table 3.3: SSS sample locations and description – MDF

Sample #	Sample ID	Description	Sample Location
1	Fresh Water	Fresh water used to rinse reclaimed sand	Spray barn on SMS
2	Recycle Water	Dilution water for SMS	Inlet to SMS
3	SLDM	Manure, urine, water and sand in a slurry	Metering system discharge
4	Reclaimed Sand	Reclaimed sand from SMS	SMS sand discharge
5	SMS	Effluent from SMS	SMS liquid outlet
6	HC Overflow	Fine effluent (overflow) from the HC	HC overflow effluent
7	HC Underflow	Coarse effluent (underflow) from the HC	HC underflow effluent

3.5.2 Manure sample collection

Fixed and volatile solid concentration results, described in Section 3.1, of samples from the SSS at GMF and MDF were used to estimate the FS separation efficiency and the change of VS attributed to sand removal. Solids data for the separation efficiency was based on manure and sand samples collected from the SSS at GMF and MDF by personnel from MSU between May of 2006 and May of 2007. Samples were collected by three employees of the Biosystems and Agricultural Engineering Department.

Feces samples at both dairy farms were collected as random samples from the freestall barn alleys. The intent of the feces samples was to characterize raw manure with no bedding. Sand-laden dairy manure samples were collected from the reception pit where scrape manure was deposited. At both GMF and MDF, SLDM manure samples were collected from the outlet of the metering device feeding manure from the reception pit into the SMS. Samples were collected when the pits were 50 to 100% full.

Effluent samples from the different levels, SMS, MINI and HC, were collected directly from the discharge, effluent, of each machine. Sand separation systems samples were collected when the machines were fully operational with discharge from both the coarse and fine flows. Operational status was determined by visual observation of the person conducting the sampling.

Sample volume or mass was generally four-times greater than what was required for laboratory analysis. Sub-samples from the farm sample were sued for analysis.

Differences in the layout and operation of the SSS at each case-study farm resulted in the farm-specific sampling protocols described in the following sections.

3.5.2.1 GMF sample collection

Samples were collected and analyzed from the locations shown in Figure 3.2 and described in Table 3.2 between May of 2006 and January of 2009. Analysis of the samples included solids characterization and particle size distribution of sand samples.

At GMF, grab samples for solids analysis were collected of feces, SLDM and from the effluent of each machine. To avoid contamination with bedding sand, feces samples were collected from freshly excreted manure patties in the freestall barn alleys. The sample protocol for feces excluded urine. Urine accounts for 1/3 of the total manure excreted by a dairy cow, feces makes up the balance (Nennich et al. 2006; Nennich et al., 2005). To account for the volume and solids contributed by urine, it is assumed to have a moisture content of 95.5% to 97%, with half of the TS contributed by FS (American Society of Agricultural and Biological Engineers, 2005; Bannink et al., 1999). Using American Society of Agricultural and Biological Engineers (2005) manure production values, the FS baseline was determined by multiplying two-thirds of the manure production (feces) by the measured FS concentration and one-third of the manure (urine) by the predicted urine FS concentration of 1.5%. Due to the operational variability of the SSS, this estimation is adequate for the objective of determining the impact of sand on AD.

Sand laden dairy manure samples at GMF were collected from the scraped manure at the end of the freestall alley, just prior to the reception pit.

Feces, urine, bedding sand and water from the drinkers is mixed during the scraping process, creating a homogenous sample at the end of the freestall alley.

Effluent samples from the different levels and machines in the SSS were collected when the units were observed to be operating at a steady-state condition. Visual observation verified that all components were operating and flow was not obstructed.

Additional samples were collected from the new sand, reclaimed sand, HC underflow and HC overflow (including tank sludge) for sand particle size analysis. Samples, 500 gram, of reclaimed sand and HC underflow were collected as grab samples in sample bags. For new and reclaimed sand samples, material was collected from several locations on the sand pile. HC underflow sand samples were collected from the discharge of the pipe carrying the full underflow stream. HC overflow samples were collected three ways; by drying 10 gallons of HC overflow liquid, from residue in the heat exchangers of the AD and from sludge accumulated in the AD tank. Sludge accumulation in the MINI's was not sampled due to the inability to collect representative samples.

3.5.2.2 MDF sample collection

Samples were collected from MDF between June of 2006 and May of 2007. At MDF, samples for solids analysis were collected from each location shown in Figure 3.3 and described in Table 3.3.

Similar to GMF, 100 mL vials were used to collect samples for solids evaluation. Sample collection occurred when operation was stable, as determined by visual observation.

3.5.3 Flow measurement

At GMF, HC overflow was the only measured flow rate. Flow meters installed at the phosphorus separation system and the AD provided the flow rate of the HC overflow. Other flow rates were unable to be measured due to a lack of flow meters and inaccessibility for direct measurement.

Manure production and bedding sand usage at GMF was estimated using data from the American Society of Agricultural and Biological Engineers (2005); Midwest Plan Services (2000). To estimate the effluent flow rates of the SMS and MINI at GMF, it was assumed that the influent to a unit was 10% greater than the fine (liquid) effluent stream. For example, sine the MINI effluent is the influent to the HC overflow, it was assumed that the MINI effluent flow rate was 110% of the HC overflow (fine effluent) flow rate. The flow rate change of 10% was predicted using data from MDF, where the fine effluent (liquid) flow rates of the SMS and HC decreased by 9% to 12% compared to the input, the change is the result of the coarse material separation.

At MDF, the flow rate of each sample location was determined by direct measurement using a 19 L bucket to collect the entire flow for a measured period of time. Direct measurement was not possible for all sample locations at GMF. Table 3.4 summaries the source of flow rate data for GMF. Similar to the sample collection process for solids analysis, measurements were made when the system operation was observed to be stable.

Table 3.4: Sample location data source – GMF

Sample #	Sample ID	Parameter FS	VS	Density	Flow Rate	Particle Size
1	New Sand	Measured	Measured	Glover, 1995	MWSP, 2000	Measured
2	Feces	Measured	Measured	ASABE, 2005	ASABE, 2005	-
3	SLDM	Measured	Measured	Gooch & Inglis, 2007	ASABE, 2005 & MWPS, 2000	-
4	SMS	Measured	Measured	ASABE, 2005	Apprixmated[2]	-
5	Reclaimed Sand	Measured	Measured	Glover, 1995	-	Measured
6	MINI	Measured	Measured	ASABE, 2005	Approximated[2]	-
7	HC Overflow	Measured	Measured	-	Measured[1]	Measured
8	HC Underflow	Measured	Measured	-	-	Measured

[1]Measure by the GMF staff using inline flow meter

[2]Used HC Overflow flow rate and increased the flow rate 10% for each SSS level

3.5.4 Density measurement

The densities of samples from each location at GMF were assumed to be similar industry data presented in American Society of Agricultural and Biological Engineers (2005), Midwest Plan Service (2000) and Gooch and Inglis (2007). At MDF, the densities were determined by weighing the bucket containing the known volume of sample used to determine flow.

3.6 Fixed solid separation efficiency evaluation

The mass balance technique described in Section 2.5 provided the basis for the FS separation efficiency at both MDF and GMF. The approach is described below.

3.6.1 Mass balance approach

A traditional mass balance evaluation, as illustrated in Figure 2.8, was completed at MDF since all of the SSS inputs and outputs could be measured (solids concentration and density). This enabled the determination of separation efficiency for each component of the MDF's SSS including the SMS, HC and SSS. Equation 2.10 was used to predict the overall separation efficiency.

3.6.2 Semi-empirical mass balance

Manure management, specifically sand separation, involves complex systems with site-specific conditions. The semi-empirical mass balance was intended to be a simple, yet robust, method for evaluating the performance of such systems operating at commercial facilities. The GMF SSS is an example of a complex SSS, consisting of several levels (SMS, MINI and HC) with multiple machines at two levels with limited access to the input and output flows of each treatment level. Utilizing a semi-empirical approach, system planners can efficiently gather important design data.

Consequently, a semi-empirical mass balance approach was developed. This approach uses standard industry values from the American Society of Agricultural and Biological Engineers (2005) and the Midwest Plan Service (2000) to estimate manure production and bedding usage to predict the flow rate of manure and SLDM. Daily manure and bedding production, along with measure FS concentration is used to establish the baseline mass of FS contributed by the manure and sand bedding (SLDM). Flow rate and FS data from the fine outlet (liquid effluent) of each SSS level were used to track the FS change, the separation efficiency. Fixed solids remaining in the effluent of the final level of the SSS were considered residual FS or residual sand. However, it is important to understand that not all of the residual FS are contributed by bedding sand. Approximately 15%, of the manure as excreted from a dairy cow is FS (American Society of Agricultural and Biological Engineers, 2005). Regardless of source, FS entering the AD are inorganic and could contribute to sedimentation and sludge accumulation, as they are not degraded biologically.

As described in Section 3.5.3, to estimate the flow rate of the SMS and MINI effluents at GMF, effluent was assumed to be less than 10% of the influent. Increasing the HC overflow flow rate by 10% provided the MINI effluent flow rate. Similarly, increasing the MINI effluent flow rate by 10% approximated the SMS effluent flow rate. An inline flow meter at the phosphorus separation system and AD provided the flow rate of the HC overflow.

Equation 2.10 was used to determine the cumulative SSS and unit separation efficiency, based on the fine material flow (overflow or effluent) of both the SMS and HC. Unit separation efficiency compared the change in the influent and effluent mass for each level of the SSS. Cumulative efficiency compared the mass of FS contributed by sand bedding to the FS contained in the effluent of each SSS level.

3.7 Particle size distribution

Sand samples (grab samples from stockpiles) for particle size distribution (PSD) were collected from GMF to achieve research objective two, determination of the residual sand characteristics. Unused (new) sand samples were collected from GMF and provided the baseline PSD to compare against sand samples collected throughout the SSS and AD. Reclaimed sand was collected from the discharge of SMS for evaluation. Hydrocyclone underflow samples were collected at the discharge of the HC.

HC overflow samples were collected by two means. Large samples of liquid HC overflow, 40 L, were collected and using a drying oven, the water was evaporated leaving only the solid residuals. As the HC overflow sample dried, residual sand accumulated near the bottom of the drying pan with a crust of manure fibers forming above the sand. Due to the inability to precisely separate the sand and manure fibers, this method was unreliable. During routine maintenance, it was discovered that small quantities of sand accumulated on the bottom of the heat pipes in the AD heat exchanger. The heat exchanger receives HC overflow prior to entry into the AD system. Residual sand samples were collected from the heat exchanger in January and May of 2008 when the heat exchanger was taken offline for service. During the service, 3 to 5 mm of sand had accumulated in the pipes.

Additional samples for PSD analysis were collected at GMF from the effluent equalization tank and AD tank #3 (tank sludge samples). These samples represent the characteristics of sand accumulation downstream of the HC. A set of samples were collected from the digester effluent equalization tank in May of 2007. The farm had begun to use the equalization tank prior to completion of the AD system. In October of 2008, AD tank #3 was taken offline and drained to allow the farm to service mixers that had failed. Only 150 mm of liquid manure was remaining. Prior to the mixer service, tank #3 was receiving half of the manure production directly from the farms each day, tank #1 received the other half of the daily manure production. Both tanks overflowed into tank #2. Qualitative measurements indicated that a thin sand/sludge layer averaging approximately 25 mm (1 in.) thick blanketed the tank bottom. Samples of the material were collected for PSD analysis from two locations.

3.8 Volatile solids loss during sand separation

Volatile solids loss during the sand separation process was determined using the semi-empirical technique developed for predicting FS separation efficiency at GMF (Equation 2.10). Sand laden dairy manure, containing feces, urine, bedding and water, was used as the baseline for the VS loss determination. The contribution of VS from new bedding sand was assumed to be negligible. Both the cumulative and unit separation VS loss were determined.

3.9 Anaerobic digester design considerations

Sand separation changes the composition of manure. Using data from GMF, design implications of anaerobic digestion were evaluated, including mixing, heating and biogas potential.

Bulk mixing power to achieve the initiation and complete scour velocity of the mean sand particle size for each sample location were calculated using Equations 2.12, 2.13 and 2.14. Each GMF digester tank has three mixers, 2 – 13 kW horizontal and 1 –10 kW vertical. Currently, GMF operates AD mixers according to the supplier recommendations, five-minutes of mixing per hour.

Heat requirements for the daily manure mass for each sample location were calculated using Equation 2.15 over a range of initial temperatures (ambient) to with the typical target (final) of 35°C.

Biogas potential was determined using Equations 2.16 and 2.17. Equation 2.16 used the daily mass of VS from each sample location to predict the gross biogas potential. Assuming biogas was approximately 60% methane (NRCS, 2007), the energy potential was determined using Equation 2.17.

CHAPTER 4: RESULTS AND DISCUSSION

In order for advanced manure treatment systems like anaerobic digestion to be successfully integrated on dairy farms using sand bedding, the impact of sand must be understood. Included is the amount of sand that can be removed using current sand separation technologies and the particle distribution of residual sand in the effluent. This research both modeled the impact and verified using an actual AD, as discussed in the subsections below.

4.1 Technique for quantification of sand separation efficiency

Grit accumulation and clogging has been cited as a leading cause of past AD failures. Consequently, determining the SSS efficiency and effluent composition are crucial for the planning and design of downstream systems. During planning for the AD at GMF, the lack of information on the efficiency of SSS and the characteristics of the residual sand limited the ability to optimize the design of the mixing system. Based on this lack of data, research objective 1 is to quantify the efficiency of SSS. The generally accepted approach is by mass balance (Svarovsky, 1990). Flow rate, density and solids data collected from MDF was used to determine if the mass balance was a practical tool to meet objective 1, measurement of the separation efficiency. However, measurement of the mass flow rate was not practical at GMF because of the inability to measure all the flow rates and operational variability, thus an semi-empirical method was developed that used a combination of measured data and industry standards. Both approaches are presented below.

Analyses of samples from the SSS's at MDF and GMF were evaluated for TS, VS and FS over an eighteen-month period. More samples were collected from the SSS at GMF than MDF due to the number of machines, six SMS and MINI, in the system. Due to the design, construction and start-up of the AD, the sampling period was also longer at GMF compared to MDF. The process flow diagram for both dairy farms was shown in Figures 3.2 and 3.3. The complete characterization data sets are included in Appendices A and B for MDF and GMF, respectively.

4.1.1 Total solids characteristics of sand separation system products

Determination of the TS is the first step in the processes of quantifying the FS and VS of a sample. The procedure for measuring solids was described in Chapter 3. Table 4.1 summarizes the TS results from the SSS at both GMF and MDF. To allow for comparison between data sources/treatment conditions, solids concentration data is summarized as a percentage in the text, equivalent to the grams of solids over the grams of the wet sample. Total solids concentration was computed using equation 3.1.

Table 4.1: Total solid concentration – GMF and MDF

Data Source	Sample Location	Mean TS (%)	Standard Deviation (%)	Median (%)	Count
GMF	Feces	14.9	2.1	14.9	68
	SLDM	28.3	11.0	30.3	69
	SMS	6.1	2.0	6.0	54
	MINI	4.9	1.3	5.0	70
	HC Overflow	4.1	1.2	4.4	40
MDF	Feces	15.2	5.0	16.9	6
	SLDM	19.0	9.4	18.8	14
	SMS	4.8	2.2	4.0	14
	HC Overflow	4.7	1.9	4.3	14

Average TS concentration of feces, as excreted, was similar for both GMF and MDF. Feces samples collected for this research excluded urine and bedding. Industry standards predict the TS of dairy cow manure, including urine, is between 12 and 13% (Midwest Plan Service, 2000; American Society of Agricultural and Biological Engineering, 2005) and consequently, the feces samples for both farms listed in Table 4.1 have slightly higher TS concentration due to the exclusion of urine.

Inclusion of bedding sand with manure resulted in an increase in TS concentration of the SLDM sample compared to the feces. SLDM from GMF had a much higher TS concentration than MDF indicating that more sand bedding may have been used at GMF. New bedding was added to the freestalls at both farms on a random schedule that ranged from days to weeks. The random bedding schedule contributed to the large TS standard deviation for SLDM. Visual observations indicated that the quantity of sand mixed with manure peaked immediately following the addition of bedding and then diminished until the next addition. The TS concentration of the samples decreased throughout the SSS (SMS, MINI, and the HC overflow), this change was caused by the addition of dilution water and the removal of FS by the SSS components.

The count is the number of sampling events for each sample location. Variability in the count is attributed to daily operational differences and the intent of the sampling event (not all sample locations or treatment levels were evaluated during each sample event).

4.1.2 Fixed solids characteristics of sand separation system products

Fixed solids results for the SSS at GMF and MDF are presented in Tables 4.2. As described in Chapter 3, the FS concentration of manure (feces + urine) was used to establish a baseline for the determination of sand separation efficiency. Equation 3.2 was used to calculate the FS concentration.

Table 4.2: Fixed solid concentration – GMF and MDF

Data Source	Sample Location	Mean FS (%)	Standard Deviation (%)	Median (%)	Count
GMF	Feces	2.1	1.0	1.9	67
	SLDM	20.0	9.7	21.6	67
	SMS	2.2	1.1	2.0	53
	MINI	1.5	0.4	1.4	70
	HC Overflow	1.1	0.5	1.2	40
MDF	Feces	3.0	1.1	2.8	6
	SLDM	12.1	7.0	10.6	14
	SMS	2.1	1.4	1.7	14
	HC Overflow	1.6	1.0	1.3	14

Differences in feed ration and water intake are the likely causes of variation in the FS concentration of feces between the two farms (Nennich, et al. 2006). Mean FS concentrations followed similar trends to TS with an increase in FS from manure to SLDM due to the addition of bedding sand and a decrease in FS with each progressive step in the SSS. The decline in FS concentration is attributed to the addition of dilution water and the removal of sand in the SSS. Similar to the TS, the high concentration of SLDM FS at GMF, compared to MDF, is attributed to differences in the quantity of bedding sand used.

4.1.3 Mass balance separation efficiency

Using the mass balance, described by Svarovsky (1990) in Equations 2.10 through 2.12, and sample collection techniques, described by Gooch (2007), the efficiency of the SSS at MDF was calculated during the spring of 2007 when the SSS was believed to be operating at equilibrium. To make these calculations, the flow rates were first determined. Included were calculations of closures to assess the quality of the measurements. Based on the densities of removed materials, the mass flow rate and closures were then calculated. This then allowed the efficiencies to be determined.

4.1.3.1 Flow rate determination

Table 4.3 summarizes the SSS measured flow rate data from MDF. To account for the intermittent operation of the piston pump feeding SLDM into the SMS and the HC, flow rates were normalized to one-hour increments shown in Table 4.3 using the measured on time of the piston-pump and HC. Sample events for the mass balance evaluation at MDF occurred on 03/05/07 (1) and 03/17/09 (2 & 3). Appendix A contains the complete data set for MDF, including FS data for the sample events.

Mass balance calculations were completed using hourly flow rate data contained in Table 4.3. The percent difference was used to compare the volume or mass of the inputs to the mass or volume of the effluents so that the mass balance closure can be determined, Equation 2.13. Input and effluent stream for the SMS, HC and SSS at MDF are shown in Figure 3.3. A mass balance closure of ±10% was established as the target based experiences with other biological and mechanical processes (Schell, et al. 2002).

Table 4.3: Sand separation system flow rate – MDF

Sample Point	Description	Sample Event 1 (m^3/hr)	Sample Event 2 (m^3/hr)	Sample Event 3 (m^3/hr)	Mean (m^3/hr)	Standard Deviation (m^3/hr)	Coefficient of Variation
1	Fresh water	0.58	0.71	0.69	0.7	0.1	10%
2	Recycled water	13.37	13.36	16.07	14.3	1.6	11%
3	SLDM	2.75	2.89	3.12	2.9	0.2	6%
4	SSS reclaimed sand	0.18	0.22	0.39	0.3	0.1	42%
5	SMS liquid effluent	15.33	14.08	19.07	16.2	2.6	16%
5a	HC input	24.23	23.72	26.43	24.8	1.4	6%
6	HC overflow	21.86	21.36	22.16	21.8	0.4	2%
7	HC underflow	0.34	1.14	0.48	0.7	0.4	65%
	SMS percent closure:	9%	21%	4%	11%	9%	
	HC percent closure:	8%	5%	14%	9%	5%	
	SSS percent closure:	-32%	-27%	-13%	-24%	10%	
	SMS dilution ratio:	4.9	4.6	5.2	4.9	0.3	

[1]SLDM flow rate based was based on the daily measured piston pump cycle time (down and up-stroke) minus the up-stroke.

[2]Cyclone flow rate was based on a measured runtime of 46 minute per hour.

Flow rate measurements presented in Table 4.3 indicated the fine effluent streams of the SMS (SMS liquid effluent) and HC (HC overflow) were reduced by 9% and 12%, respectively, compared to the influent flow rate.

Successful mass balance closures were achieved for two out three attempts for each level of the SSS, SMS and MINI. The successful mass balance closures all exceeded 100%, indicated that the influent flow rate exceeded effluent. This could be attributed to variations in the flow rate of the coarse material separated in the SMS and HC. Coarse material flow rates from the SMS (SSS reclaimed sand) and HC (HC underflow) had the largest coefficients of variation.

None of the SSS mass balance attempts closed within the target of ±10%. All the SSS closure attempts indicated that effluent flow rates exceeded the influent (<100%), a result opposite of the machine level. Intermittent operation of the HC, resulting in collection and temporary storage of the SMS effluent, is the likely reason for the effluent flow rate exceeding influent.

The dilution ratio, recycled water to SLDM, is included in Table 4.3. MDF used an average dilution ratio nearly five times that of the 1 to 1 dilution ratio suggested by Wedel (1995) as a minimum for sand separation. Due to the closed loop recycle of solid-liquid separator effluent, dilution water at MDF had a relatively high mean TS concentration, 4.3% (Appendix A), causing the equipment supplier to recommend operating the system at a higher dilution ratio.

Tables 4.4 and 4.5 summarize the material density and mass flow rate for each sample location.

Table 4.4: Sand separation system material density – MDF

Sample Point	Description	Sample Event 1 (kg/m³)	Sample Event 2 (kg/m³)	Sample Event 3 (kg/m³)	Mean (kg/m³)	Standard Deviation (kg/m³)	Coefficient of Variation
1	Fresh water	997	1,005	1,000	1,000	4	0%
2	Recycled water	1,015		1,037	1,026		
3	SLDM[1]	1,092		1,003	1,048		
4	SSS reclaimed sand	2,038	1,708	1,617	1,787	221	12%
5	SMS liquid effluent	1,024	1,059	1,035	1,039	18	2%
5a	HC input[2]	1,024	1,059	1,035	1,039	18	2%
6	HC overflow	1,026	1,004	1,024	1,018	12	1%
7	HC underflow	1,653	1,149	1,371	1,391	253	18%

Table 4.5: Sand separation system mass flow rate – MDF

Sample Point	Description	Sample Event 1 (kg/hr)	Sample Event 2 (kg/hr)	Sample Event 3 (kg/hr)	Mean (kg/hr)	Standard Deviation (kg/hr)	Coefficient of Variation
1	Fresh water	580	710	691	660	70	11%
2	Recycled water	13,573	10,987	16,669	13,743	2,845	21%
3	SLDM[1]	3,007	2,694	3,127	2,943	223	8%
4	SSS reclaimed sand	361	384	629	458	148	32%
5	SMS liquid effluent	15,695	14,913	19,730	16,779	2,585	15%
5a	HC input[2]	24,813	25,125	27,344	25,761	1,380	5%
6	HC overflow	22,443	21,449	22,689	22,194	656	3%
7	HC underflow	564	1,306	654	841	405	48%
	SMS percent closure:	9%	3%	4%	5%	4%	
	HC percent closure:	7%	9%	15%	10%	4%	
	SSS percent closure:	-33%	-52%	-14%	-33%	19%	

[1]SLDM flow rate based was based on the daily measured piston pump cycle time (down and up-stroke) minus the up-stroke.

[2]Cyclone flow rate was based on a measured runtime of 46 minute per hour.

Similar to the flow rate results, all of the SMS and two of the HC mass flow rate closure attempts shown in Table 4.5 closed to within ±10% while the SSS mass flow rate measurements did not.

Table 4.6 summarizes the FS mass flow rate for the various sample locations associated with the SSS at MDF. The FS mass flow rate was determined by multiplying the mass flow rate (Table 4.5) by the FS concentration (Appendix A).

Table 4.6: Sand separation system fixed solids mass flow rate – MDF

Sample Point	Description	Sample Event 1 (kg/hr)	Sample Event 2 (kg/hr)	Sample Event 3 (kg/hr)	Mean (kg/hr)	Standard Deviation (lb/hr)	Coefficient of Variation
1	Fresh water	-0.2	1.1	0.2	0.4	0.7	174%
2	Recycled water	188.5	183.2	292.6	221	62	28%
3	SLDM[1]	250.0	375.1	234.7	287	77	27%
4	SSS reclaimed sand	209.3	268.3	469.9	316	137	43%
5	SMS liquid effluent	238.6	411.6	452.2	367	113	31%
5a	HC input[2]	377.2	693.5	626.7	566	167	29%
6	HC overflow	240.3	381.8	324.2	315	71	23%
7	HC underflow	229.1	445.1		337		
	SMS percent closure:	33%	32%	-75%	-3%	62%	
	HC percent closure:	-24%	-19%		-22%		
	SSS percent closure:	-3%	-16%	-51%	-23%	25%	

[1]SLDM flow rate based on the measured piston pump downstroke, upstroke deducted

[2]Cyclone flow rate based on measured runtime of 46 minute per hour

Only one successful FS mass balance closure was achieved for sample event 1. The poor FS mass flow rate closures were assumed to be caused by the intermittent and unstable operation of SSS components, primarily the piston pump and HC.

4.1.3.2 Separation efficiency

Equation 2.11 compares the mass of the coarse FS material removed by the SSS to the mass of the influent FS to determine separation efficiency. Table 4.7 summarizes the results. Fixed solid concentration for the HC sample event 3 was not reported due to a laboratory error. Mass balance separation efficiency calculations assumed that the change in FS throughout the SSS is caused by the removal of sand.

Table 4.7: Fixed solids separation efficiency – MDF

Component	Sample Event			Mean	Standard Deviation
	1	2	3		
SMS:	31%	27%	89%	49%	35%
HC:	61%	64%		62%	
SSS:	48%	48%	89%	62%	24%

Mean separation efficiency of the SSS, at only 62%, was less than reported by Wedel and Bickert (1998). If the efficiency results were accurate, accumulation of sand in the storage would be anticipated. However, discussions with the owner/operator of the dairy indicated that sand accumulation downstream of the SSS did not occur (Minnis, 2008). The contrast of the poor separation efficiency to the lack of downstream sand accumulation evidence indicates that the direct mass balance approach may have limitations when it comes to predicting separation efficiency. Unstable operation of the SSS at MDF is believed to be the major limitation impacting the ability to conduct direct mass balance measurements of separation efficiency. Consequently, an in depth study of MDF operations was conducted.

An improperly sized feed pump caused the HC to cycle on and off several times each hour. Time measurements collected during the sampling events and discussions with the operator indicate that the HC operated approximately 45 min of each hour of SSS operation. The HC underflow discharged into the dilution pool of the SMS, contributing approximately 18.9 L/min with a FS mass of 18.2 kg or 6% of the average SMS influent mass. When the HC cycled off, the contents within the unit emptied completely through the underflow discharging between 132 and 151 L (131 to 150 kg) of manure slurry instantaneously, creating a short, but substantial increase in the mass flow entering the SMS, upwards of 45% of the normal SMS influent FS mass. This instantaneous increase in HC underflow could potentially interrupt the flow of reclaimed sand from the SMS temporarily. This could occurred because the auger used to excavate sand from the SMS rides on a bed of sand, approximately one inch thick, that forms between the auger flighting and the SMS body, eliminating wear due to metal on metal contact. The velocity of the sudden HC underflow discharge when the unit cycled off had the potential to erode the sand bed in the SMS, interrupting the flow of reclaimed sand until the bed was reestablished.

At MDF, operation of the piston pump feed system was another SMS input with a variable flow rate. Manure was metered into the SMS only during the down stroke of the piston pump. During the up stroke, the piston refilled. The SLDM transferred into the SMS by the piston pump contributed about 6.4 L/min. with a mass of 2.9 kg, equivalent to 33% of the input FS into the SMS. Temporarily interrupting the flow of SLDM directly impacts the flow of reclaimed sand from the system at any instance.

To further verify that the SSS never reaches static equilibrium, the effluent flow rate of the SMS was measured every 1.5 to 2 minutes for a period of 45 minutes. Each time the flow rate was measured, the density and solids concentration of the effluent was also determined. Four measurements were made while the piston pump was on the up-stroke and 3 with the HC not operating. No measurements were taken when both the piston pump and cyclone were not operating. The SMS effluent flow rate data is contained in Appendix A. Figure 4.1 graphically displays the flow range (5.7 to 9.9 L/s during the 45-minute sample period). No pattern or consistency relating to the operation of the piston pump or HC was observed.

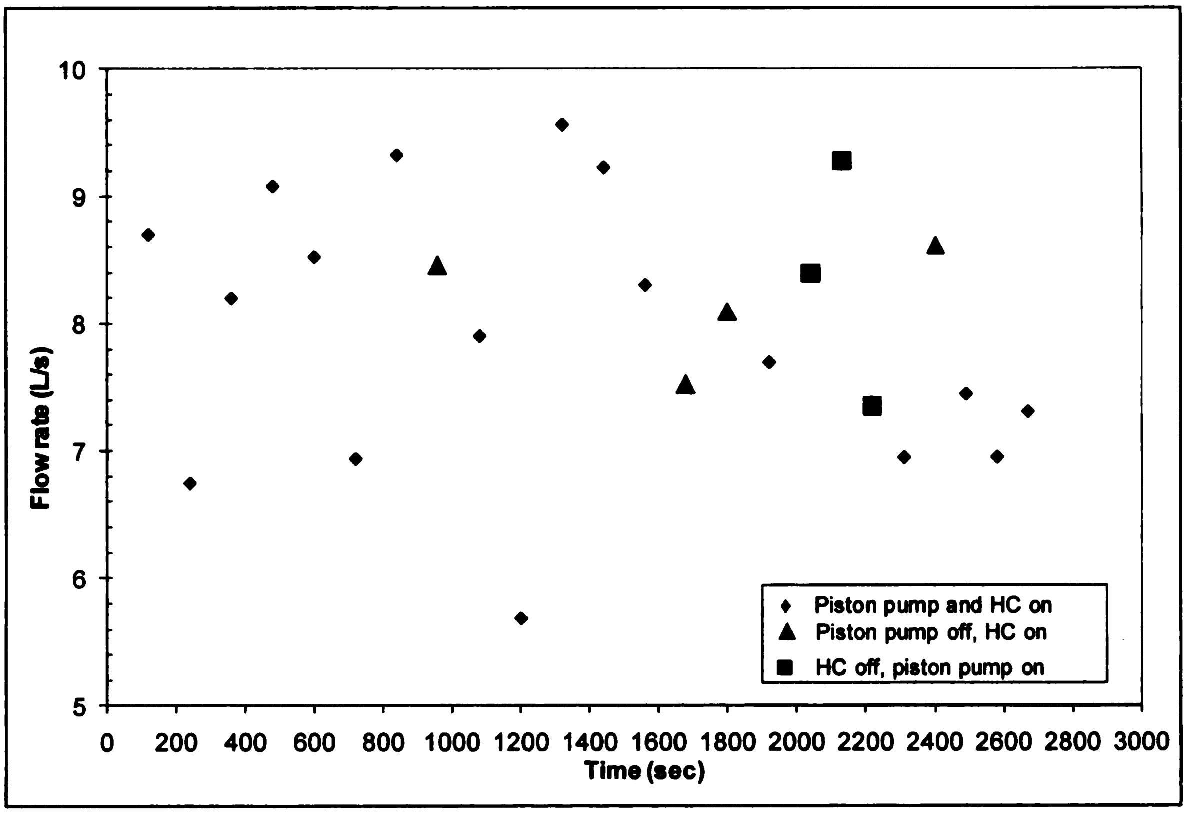

Figure 4.1: Sand manure separator effluent flow rate – MDF

Changes in the recycle water flow rate contribute to variations in the SMS effluent flow rate. Recycle water flow rate at MDS was controlled using a bypass system with a valve restricting flow in the line leading to the SMS, excess water flow freely through the bypass line. The position of the valves was established by the SSS operator, however at times valve was known to become partially clogged with manure fibers and debris, causing changes in the flow rate.

The mass balance approach to determining FS separation efficiency was unsuccessful because the SSS never operated consistently. On/off cycles of several system components and variability of the flow rate contributed to unsteady operation. The inability to successful use the mass balance technique for even a simple system consisting of two technology levels with only one SSS operating at each level and warrants investigation of an alternative approach.

4.2 Semi-empirical mass balance separation efficiency

Limitations with the mass balance approach, as demonstrated at MDF, led to the development of a semi-empirical mass balance approach that used a combination of measured and established industry data to predict the separation efficiency. The semi-empirical technique used the daily effluent mass flow rate and the FS concentration for each component of the SSS to determine the mass of FS remaining in the effluent (residual sand) contributed by bedding sand and the FS separation efficiency. Because of the complexity at GMF, this technique is believed to be the only valid technique to estimate of the sand separation efficiency.

Data collected at GMF during the design, construction and startup of the AD were used for the semi-empirical mass balance. As discussed in Chapter 3, the SSS at GMF consisted of six SMS-MINI combinations feeding into a single

HC. Flow was only measured at a single location, HC overflow entering the digester and phosphorus separation process.

4.2.1 Semi-empirical mass balance parameter specification

To complete the semi-empirical mass balance, several key parameters were either assumed or determined by measurements.

Due to the inability to accurately measure manure production and bedding usage, both were assumed to be similar to industry standards (American Society of Agricultural and Biological Engineers, 2005; Midwest Plan Service, 2000). The standards are developed by industry experts using data collected from numerous research trials around the United States. Both standards are used in Michigan for technical and regulatory guidance (Michigan Department of Environmental Quality, 2006; U.S. Department of Agriculture, 2009). Table 4.8 summaries the standard production values on a per cow basis and the bulk density of different system inputs and products. Table 3.4 indicates which data was measured and which was based on industry standards at GMF, the case study farm used for the semi-empirical mass balance.

Table 4.8: Standards used in the semi-empirical mass balance evaluation

Parameter	Value	Unit	Source
Lactating cows	2,900		
Dry cows	300		
Lacating cow manure	68	kg/d/cow	ASABE, 2005
Dry cow manure	38	kg/d/cow	ASABE, 2005
Bedding	22	kg/d/cow	MWPS-18, 2000
Bulk density of manure	1,001	kg/m3	MWPS-18, 2000
Bulk density of SLDM	1,163	kg/m3	Gooch and Inglis, 2007
Bulk density of sand	1,696	kg/m3	MWPS-18, 2000

The primary component of FS above the base line level in feces was assumed to be sand. Also, changes in FS throughout the sand separation process were assumed to be sand. This assumption was based on the measure difference in the FS concentration of feces compared to SLDM (Table 4.2).

FS from the dilution water was assumed to be negligible. The basis was that the TS concentration in the recycled dilution water used at GMF ranged from 1.05% to 1.95% (Green, 2005), with a FS concentration range of 0.16% to 0.3%.

Effluent flow rate for each component of the SSS was assumed to be 10% less than the influent flow rate. Section 3.5.3 provides a detailed discussion of the flow rate determination for the SMS and MINI. This assumption was based on findings from MDF which indicated that the SMS and HC effluent (fine material) flow rates were between 9% and 12% less, respectively, than the influent flow rates (Table 4.3).

Using the industry data in Table 4.8, the mass and volume of manure at each GMF sample location were calculated (Table 4.9). Table 4.9 summarizes the theoretical and measured volumetric and mass flow rate of each sample location at GMF.

Table 4.9: Mass and flow rate data – GMF

Sample Location	Flow Rate	
	Volume	Mass
	(m^3/d)	(kg/d)
Manure	208	208,600
Bedding sand	42	71,273
SLDM	241	279,873
SMS	504	504,497
MINI	458	458,634
HC overflow	416	416,940

Based on the mass flow data in Table 4.9 and the FS data in Table 4.2, the mean mass of FS contained in the effluent of each step in the treatment process is presented in Table 4.10. The 95% confidence interval for the FS mass is also included in Table 4.10.

Table 4.10: Overall FS mass by treatment step - GMF

Treatment	Mean	Standard Error	95% Confidence Limit		Count
			Lower	Upper	
	(kg/d)	(kg/d)	(kg/d)	(kg/d)	
Manure	3,978	1,455	1,926	8,217	68
SLDM	43,887	7,975	28,821	66,828	64
SMS	10,199	2,373	6,299	16,515	50
MINI	6,402	1,728	3,709	11,049	67

Mean mass flow rates of the overall data in Table 4.10 for manure, SLDM, SMS and MINI represent samples from the six sample locations (machines) at

SMS and MINI level of the SSS. Whenever possible, samples were collected from all SSS levels and machines during a sampling event. However, due to system management and sample event goals, not all of the SSS components were evaluated during all of the sampling events.

For all sample locations, except manure, the mass of the FS in Table 4.10 was determined by multiplying the mass flow rate in Table 4.9 by the FS concentrations (Table 4.2). To compute the FS contributed by manure in Table 4.10, two-thirds of the daily manure excretion was assumed to be feces and one-third urine (Nennich et al., 2006; Bannink et al. 1999). The FS concentration of feces was measured (Table 4.2), while the FS concentration of the urine was assumed to be 1.5% (Bannink, 1999).

Factors contributing to the change in fixed solids of samples collected from GMF were evaluated using a SAS mixed model with both fixed and random effects. Fixed effects included the following.

- Management: operational differences between Farms 2 and 3.
- Treatment: compared feces, SLDM, SMS, MINI and HC.
- Interaction of management and treatment.

Machine was considered a random effect, which represented the six SMS and MINI operating as part of the SSS (Figure 3.1). Section 3.4 provides additional details on the statistical evaluation of the change in FS.

The mass of FS for feces, SLDM, SMS and MINI from GMF were not normally distributed. Consequently, a logarithmic transformation was used to fit the data to a normal distribution curve. Outliers, values distant from the critical mass of data, including SLDM from Farm 3, Machine 6 on 07/05/06 and 03/23/07, Feces from Farm 2, Machine 4 on 07/05/06 and SMS from Farm 2, Machine 4 on 03/23/07 were deleted. A test of the fixed effects found treatment to be the only statistically significant factor contributing to the change in FS at $\alpha=0.05$ ($p \leq 0.0001$). Management and the combination of management and treatment were not significant at $\alpha=0.05$, resulting in a $p=0.7464$ and $p=0.7912$, respectively. This supported the assumption that changes in the mass of FS throughout the SSS are attributed to treatment.

Comparing the least square means for the different treatment levels indicated that the mass of FS in feces compared to SLDM ($p \leq 0.0001$) and SLDM compared to SMS ($p \leq 0.0001$) were statistically different. However, FS mass of the SMS compared to MINI ($p=0.1768$) was not statistically different. The result indicated that the SMS as a system was the only statistically important level of treatment. ANOVA and least square mean tables are included in Appendix B.

The large increase in the mass of FS from manure to SLDM results from the addition of bedding sand. Similarly, the decreasing mass of FS from SLDM to SMS to MINI is from the removal FS. Differences in the management (Farms 2 and 3) and the sample location (machine) were not considered in the empirical mass balance because those factors were not found to be statistically important in explaining the change in FS throughout the SSS, as discussed above.

Hydrocyclone overflow data resulted from samples collected from the single machine (Figure 3.1). To evaluate the impact of the HC on the mass of FS remaining in the manure, data from the other treatment levels was averaged for sample events when the HC was operational. Averaging results by sample event was done to allow for direct comparison with the HC and because the effects of machine and management were not significant for changes in FS. Table 4.11 summarizes the mean and 95% confidence intervals for the daily MINI and HC data, as well as the other treatment levels. A check of the residuals found that the data was normally distributed. A test of the single fixed effect, treatment, found a statistically significant difference in the FS of the HC overflow compared to the MINI at α=0.05 (p- =0.0017), indicating that the HC had a statistically important effect on the mass of FS in the manure. ANOVA and least square mean tables for FS mass are contained in Appendix B.

4.2.2 Sand separation efficiency

Svarovsky's (1990) cumulative separation efficiency equation for fine particulate (Equation 2.12) was used to determine cumulative FS separation of the SSS. Since management and machine effects were not found to have a significant effect on the change of FS mass, the mean of the treatment levels for a given sample event (sample day) was used to determine the separation efficiency. Table 4.11 summarizes the FS mass data for the twelve sample events where all components were sampled. Using the daily mean of the FS mass for each sample location allowed for a direct comparison of HC to the other treatment levels with multiple machines.

Table 4.11: Daily fixed solids mass data – GMF

Treatment Level	Mean (kg/d)	Standard Deviation (kg/d)	Median (kg/d)	Count
Manure	3,705	571	3,847	12
SLDM	52,716	11,240	56,003	12
SMS	9,878	2,173	10,018	12
MINI	6,695	787	6,504	12
HC Overflow	5,334	621	5,094	12

The difference in the FS mass of SLDM and Manure provided the baseline mass of FS contributed by the sand bedding. That baseline was used to determine the cumulative FS separation efficiency. Table 4.12 summarizes the mean FS separation efficiency at each treatment level. The 95% confidence interval is also shown in Table 4.12.

Table 4.12: Cumulative fixed solid separation efficiency – GMF

Treatment Level	Mean (%)	95% Confidence Limits	
		Lower (%)	Upper (%)
SMS	87	83	90
MINI	94	92	95
HC Overflow	97	96	98

Figure 4.2 graphically displays the mean cumulative FS separation efficiency with the 95% confidence interval for the three levels of the SSS. The 95% confidence interval of the SMS was within the range predicted by Wedel and Bickert (1998).

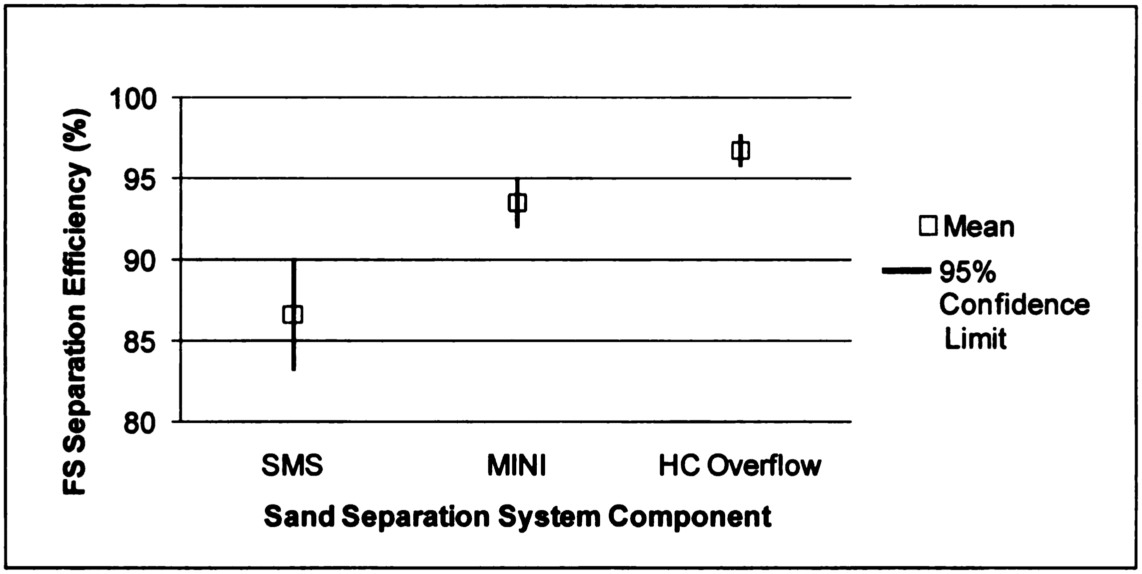

Figure 4.2: Cumulative fixed solid separation efficiency – GMF

Data in Table 4.13 compares the separation efficiency for each level of the SSS. Table 4.13 was constructed with the data shown in Table 4.11. Similar to the cumulative separation efficiency, treatment level efficiency was calculated using Equation 2.10. To determine the treatment level efficiency, the FS mass of the component influent (effluent from the previous unit) was used. Compared to the SMS, the separation efficiencies of the MINI and HC were significantly less. Figure 4.3 depicts the mean and confidence interval for the FS separation efficiency of each SSS treatment level.

Table 4.13: Treatment level fixed solid separation efficiency – GMF

Treatment Level	Mean (%)	95% Confidence Limits	
		Lower (%)	Upper (%)
SMS	87	83	90
MINI	46	36	55
HC Overflow	47	33	60

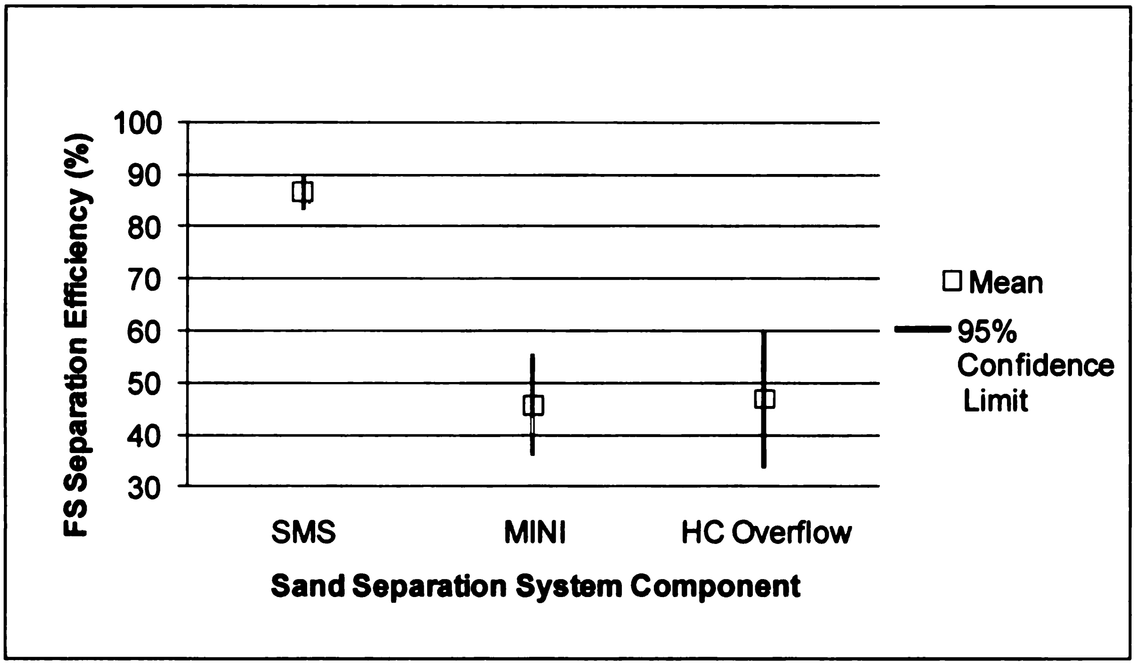

Figure 4.3: Treatment level fixed solid separation efficiency – GMF

The semi-empirical mass balance approach estimated sand separation efficiency values similar to those reported by Wedel and Bickert (1998). Specifically, the SMS separation efficiency had a 95% confidence interval of 83% and 90% separation efficiency of the bedding sand from SLDM. Incremental improvements in the separation efficiency were observed for each component of the SSS, resulting in a cumulative FS separation efficiency with a 95% confidence interval of 96% to 98%.

Based on the confidence interval of the FS separation efficiency determined by the semi-empirical evaluation, the mass of residual sand in the manure after the SSS was in the range of 1,564 kg/d to 2,994 kg/d. This assumed the GMF uses 71,273 kg/d of bedding sand (Midwest Plan Service, 2000). Determining the FS separation efficiency was an important factor for predicting sand accumulation potential (quantity) in the digester at GMF. However, the PSD of this residual FS must be examined to determine if the mixing system was capable of keeping residual sand suspended in the AD at GMF.

Accuracy of the semi-empirical technique was influenced by the manure production and sand usage data sets used to estimate the baseline FS contributed by manure and bedding sand, the ability to only track the separation of FS contributed by sand and the management of the SSS. Manure production and sand usage are highly variable due to differences in environmental conditions and management, resulting in an error range of ±30% (Midwest Plan Service, 2000). Similarly, urine production and composition is variable depending on water intake, ration, feed quantity and milk production (Nennich et al., 2006).

Fixed solids provide the simplest most logical method for tracking sand changes in manure and the semi-empirical mass balance method provided useful information for system planners. However, simply tracking the FS change does not provide sufficient information for planners of AD or other advance treatment systems. For that reason particle size data of new sand, sand removed and residual sand was also investigated to provide additional measure for tracking the fate of bedding sand. Particle size data also provides important information to system planners sizing mixing systems to address sedimentation.

4.3 Particle size distribution of sand separation products

Understanding that the HC overflow did contain residual sand, determination of the PSD of residual sand was needed to evaluate the potential for sedimentation in the downstream processes, in particular the AD tanks. This data will enable the determination if the AD mixing system is sufficient to achieve the scour velocity of the mean particle size remaining the HC overflow so that sedimentation does not occur.

As described in Chapter 3, samples were collected from new sand, reclaimed sand, HC Underflow, HC overflow and sludge accumulation in the digester tanks at GMF for PSD evaluation. Figure 3.2 and Table 3.4 indicate the locations samples were collected to analyze for PSD. New sand samples served as the baseline.

Table 4.14 summarizes the results of the PSD analysis as the mean percent passing of particles through an array of sieves with decreasing opening sizes (the complete PSD data set including statistical analysis is contained in Appendix D). The sieve opening size in Table 4.14 represents the maximum particle diameter passing the given sieve calculated using equation 3.6.

Table 4.14: Mean sand particle size distribution – GMF

Sieve #	Sieve Opening (mm)	Mean Percent Passing				
		New Sand	Reclaimed Sand	HC Underflow	HC Overflow	Tank Sludge
4	4.75	100	99	93	98	96
8	2.36	88	83	87	96	92
16	1.18	69	60	77	94	86
30	0.60	45	33	61	89	78
50	0.30	12	4	37	72	63
100	0.149	2	0	10	39	37
200	0.074	1	0	2	10	9
Pan		0	0	1	-1	-1
Number of Samples		6	7	5	5	4

Based on the PSD, new sand from GMF was classified as concrete sand according to ASTM (2006) Standard, Table 2.3. According to the ASTM (2006), AASHO (1991) and USDA (1993) standards, the sand remaining in the manure stream after the HC was classified as fine sand to very fine sand.

Figure 4.4 graphically displays the PSD data presented in Table 4.14. The X-axis represents the particle size (diameter) and the Y-axis indicates the percentage of the sample that passed through that size sieve. Using new sand as the baseline, curves to the right represent coarser material and curves to the left, material that is finer than new sand. Reclaimed sand from the SMS was coarser than the new sand, with a lower percent pass at all of the measured particle sizes. Specifically, sand reclaimed by the SMS contained less than 4% (by mass) particles with a diameter of 0.3 mm or less, compared to new sand which contained 12%. This signifies that the SMS was more effective at removing coarse sand particles leaving finer sand particle in the manure stream (SMS effluent).

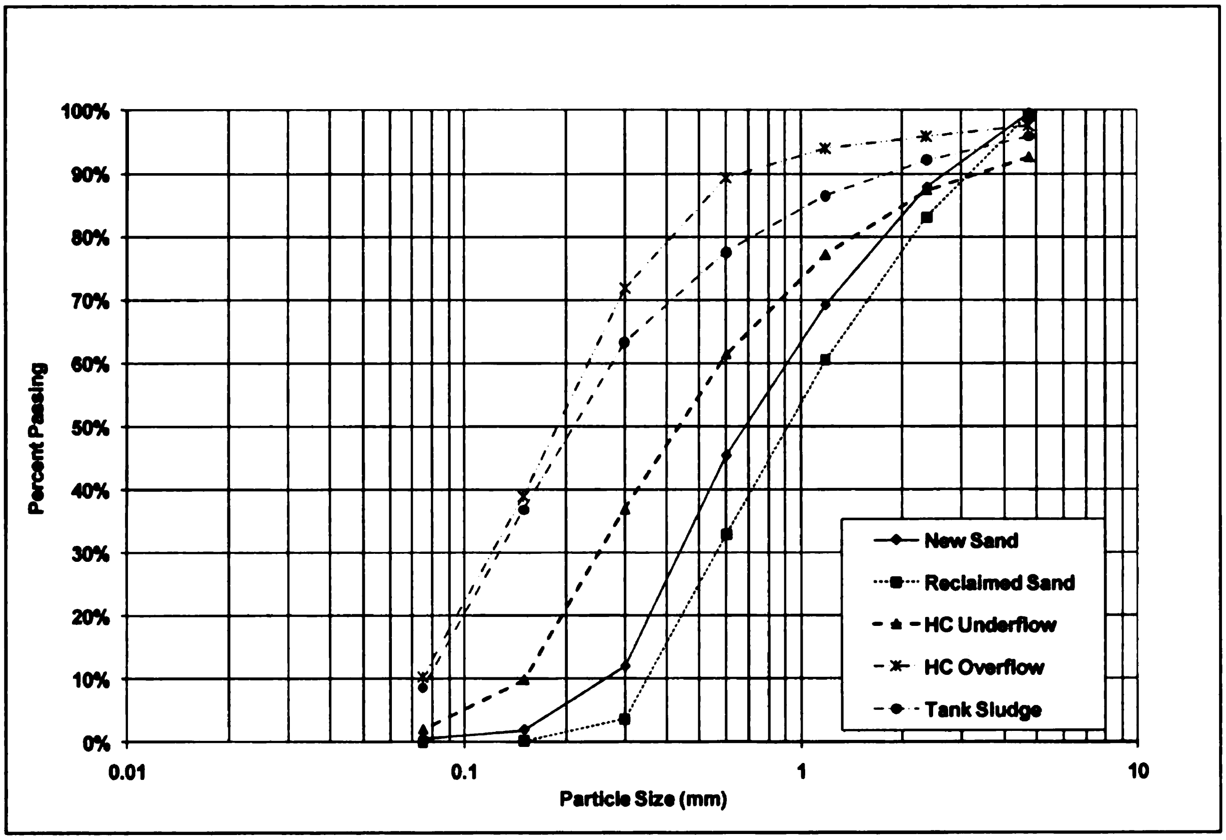

Figure 4.4: Average sand particle size distribution – GMF

The PSD of HC underflow was visibly finer than both new and reclaimed sand. These findings for the SMS and HC support the statement in Zimmels (1984) that individual separation technologies are only effective over a fraction of the sand particle size range. By design, the HC separator at GMF was intended to separate finer (smaller) sand particles than the SMS and MINI in order to reduce the residual sand in the manure stream entering the AD.

Interpolating the mean particle size of residual sand in the HC overflow and in the tank sludge resulted in diameters of 0.18 mm and 0.21 mm, respectively. This resulted in an average PSD of residual sand of 0.195 mm. In comparison, the mean particle size of new sand was 0.6 mm. This reduction indicated that the SSS was effective at removing coarse sand particles from the manure.

4.3.1 Settling and scour velocity of sand

The mean particle size (50% passing) for each sample location was interpolated from the graph shown in Figure 4.5. Scour velocity (Equation 2.7) was calculated for new and residual sand using the mean particle size, results are shown in Table 4.15. Data for new sand is included for comparison purposes.

Table 4.15: Residual sand scour velocity – GMF

Sample Location	Mean Particle Size (mm)	Scour Velocity Initiation (m/s)	Scour Velocity Complete (m/s)
New Sand	0.69	0.26	1.15
HC Overflow	0.18	0.13	0.59
Tank Sludge	0.21	0.14	0.64

Compared to new sand to the mean particle size of residual sand in the HC overflow and found in the tank sludge was reduced by three quarters. This particle size reduction reduced the settling velocity by an order of magnitude and the scour velocity (initiation and complete) by half compared to new sand.

4.3.2 Residual sand impact on anaerobic digester mixing system design

Anaerobic digester mixing systems are typically intended to bring viable bacteria into contact with substrate, minimize heat and solids gradients and to release biogas from the slurry (Hoffman et al., 2008). Additionally, the mixing system at GMF, as with any dairy farm using sand bedding, also needs to prevent grit accumulation.

Annually, GMF used an estimated 26,000 metric tons of bedding sand, occupying a volume equivalent to 15,300 m^3/yr. Theoretically, if no sand separation was in place at GMF, bedding sand could fill the 10,200 m^3 anaerobic digester in less than five months. Based on the cumulative separation efficiency presented in Table 4.12, the mass and volume of residual sand in the HC overflow is between 1,564 kg/d to 2,994 kg/d and 0.92 m^3/d and 1.77 m^3/d, respectively. In theory, if all the residual sand accumulated in AD tanks it would fill the tanks in the range of 16 to 30 years. To prevent this sedimentation, the power in the AD mixing system must maintain produce a minimum velocity that exceeds the initiation scour velocity of residual grit.

Each digester tank at GMF was constructed with three submersible propeller type mixers, based on the German technology suppliers experience with systems in Europe. Two 13 kW mixers were positioned to provide 26 kW of total horizontal mixing, while one 10 kW mixer was aligned vertically (Figure 4.5). Scour velocity as determined using Shields' (Equation 2.5) only considers the horizontal velocity (Wedel, 2000).

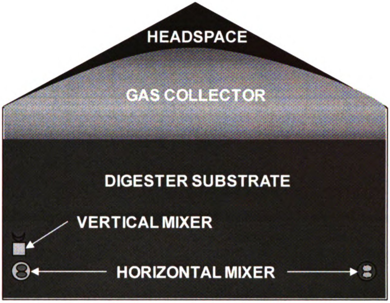

Figure 4.5: Anaerobic digester mixer configuration – GMF

For comparison purposes, Table 4.16 summarizes the minimum theoretical power required to initiate and develop complete scour for the mean sand particle size found in HC overflow and tank sludge. Again, new sand was included for comparison purposes. The bulk mixing power required was determined using Equations 2.16 through 2.18, with the scour velocity of the average particle size for each sample location (Table 4.15) substituted as the velocity in Equation 2.17. A mixing time of five minutes per hour, typical at GMF, was used, as recommended by the technology supplier and supported by Hoffmann et al. (2008). Annual operating cost of the mixing operation was calculated assuming 365 days of operation and an electricity purchase price of \$0.10 per kWh.

Table 4.16: Power required to achieve scour velocity of sand – GMF

Sample Location	Mean Particle Size (mm)	Power Initiation (kW)	Power Full (kW)	Operating Cost Initiation (yr)	Operating Cost Full (yr)
New Sand	0.69	0.75	15	$55	$1,090
HC Overflow	0.18	0.19	4	$14	$284
Tank Sludge	0.21	0.23	5	$17	$332

The power required to achieve full scour ranged from 4 kW for the mean sand particle contained in HC overflow to 15 kW for new sand. Based on the EPA (1979) recommendation, the AD tanks at GMF should have between 18 and 27 kW of mixing power to suspended residual sand contained in the influent. The, actual horizontal mixer power was GMF 26 kW. Due to the change in the mean particle size resulting from sand separation, the power required for full scour of residual sand in HC overflow is one fourth that of new sand. It should be noted that while the mixer power installed at GMF is adequate for the mean particle size of new sand, it does not have sufficient power to completely scour sand grains greater than 1.18 mm. New sand used for bedding at GMF contained over 30% particles greater than 1.18 mm, compared to only 6% of the residual sand in HC overflow. Consequently, the mixing system installed in the AD system at GMF is capable of fully scouring 94% of the residual sand. The cost to operate the mixing system was less than $1,000 annually. Even with sufficient power, improper mixer selection, configuration and operation may still result in sedimentation in the AD tanks as low velocity (dead) zones can account for a large portion of the tank volume (Wu and Chen, 2007).

4.3.3 Verification of sand accumulation predictions

Consequently, the semi empirical mass balance approach used to determine the SSS efficiency combined with the modeling of mixing indicated that sand accumulation in the GMF AD tanks should not occur. In October of 2008, after fifteen months of operation, AD tank #3 at GMF was emptied for maintenance on the mixers (a detailed explanation of the maintenance event is contained in Chapter 3). This provided the opportunity to verify the mixing system predictions in regards to sand accumulation.

Prior to the maintenance, tank #3 had received half of the digester feedstock each day, resulting in a load of FS from residual sand of between 713 kg/d to 1,425 kg/d (0.46 m^3/d to 0.89 m^3/d). In theory, if no mixing were provided and all residual sand settled, a layer of residual sand 160 to 310 mm thick could have accumulated over the fifteen-month operating period.

During the mixers repairs, the tank volume was lowered so that approximately 150 mm of liquid remained in the tank. By probing accumulated sediment, it was approximated that sludge accumulation (sand and manure) was approximately 25 to 50 mm thick (Green, 2008). For safety reasons, exact measurements could not be taken. Grab samples of the sediment were collected from two locations for PSD analysis, results are presented as tank sludge in Figure 4.4 and Table 4.14. This verified that the combination of SSS and mixing had achieved the goal of minimizing sand settling in the tanks and the modeling approach was accurate.

4.4 Volatile solids loss due to sand separation

The mass of VS contained in feedstock directly correlates to the potential biogas production under anaerobic conditions (U.S. Department of Agriculture, 2007). Consideration of the impact of pretreatment of manure, sand separation, on the mass of VS is essential for predicting the impact on biogas production. Volatile solids loss is an unintended consequence of sand separation. Removal of VS with FS and increased aeration are two effects that contribute to any reduction in the manure VS mass.

4.4.1 Volatile solids characteristics of sand separation products

Volatile solids concentrations for each SSS sample location at GMF are summarized in Table 4.17. Equation 3.3 describes how the VS concentration is determined. The feces sample excluded urine, spilled water and sand bedding so consequently, using this material for comparison is not warranted. Therefore, SLDM was used as the baseline for comparing the change in VS throughout the SSS at GMF.

Table 4.17 Sand separation system volatile solid concentration – GMF

Data Source	Sample Location	Mean VS (%)	Standard Deviation (%)	Median (%)	Count
GMF	Feces	12.6	1.7	12.5	68
	SLDM	7.6	1.4	8.0	69
	SMS	3.7	0.9	3.8	54
	MINI	3.4	1.0	3.5	70
	HC Overflow	3.0	1.1	3.2	40

Unlike FS, manure is the primary source of VS in manure. The mass of volatile solids in manure is influenced mainly by the ration fed to the cattle. Rations generally remain stable for long periods (months), which was the case during the research. The addition of recycled dilution water during the sand separation also contribute to changes in the mass of VS. Dilution water used in the SMS contained less than 2 % TS and was consistent over long time intervals at GMF due to the operation of the phosphorus separation system.

VS data from GMF was evaluated to determine which factors contributed to changes in the mass of VS in the manure and if it was statistically significant. Fixed and random effects, as described in Section 4.1.2, were evaluated using a SAS mixed model. Treatment, management and combination of treatment and management were not found to be statistically significant effects causing changes in the VS of the manure stream at α=0.05 with values of p=0.2413, p=0.1995 and p=0.7022, respectively. Comparing the treatment least square means indicated no significant difference in the mass of VS of SMS compared to SLDM (p=0.3187) or MINI compared to SMS (p=0.2821). Table 4.18 shows the mean mass of VS at each treatment level in addition to the 95% confidence limit.

Table 4.18: Overall VS mass by treatment step – GMF

Treatment	Mean (kg/d)	Standard Error (kg/d)	95% Confidence Limit Lower (kg/d)	Upper (kg/d)	Count
SLDM	21,259	1,326	4,410	38,109	64
SMS	18,738	1,347	1,626	35,851	50
MINI	15,846	1,321	-937	32,629	67

Similarly, a test of the single fixed treatment effect, HC overflow compared to the MINI, did not contribute to a statistically significant difference in the mass of VS at $\alpha=0.05$ ($p=0.2568$). ANOVA and least square mean tables for VS are contained in Appendix B. While changes in the VS mass throughout the SSS were not found to be statistically significant, the data does indicate that smaller mass of VS remained in the manure following sand separation.

4.4.2 Volatile solids changes due to sand separation

Techniques described in Section 4.2.2 for use in determining the separation efficiency of FS were used to track the change in the mass of VS. Again, since management and machine were not found to have a significant effect on the change of VS mass, the mean of individual machine samples at each treatment level for a given sample event was used to determine the change in VS mass. Table 4.19 summarizes the mean and confidence intervals of the daily averaged MINI data and the HC overflow. While Table 4.18 evaluates all the data for SLDM, SMS and MINI, Table 4.19 contains the only the data for sample events that included the HC. Compared to FS, VS had one less sample event due to an isolated laboratory problem. Using the daily mean of the VS mass for each sample location allowed for a direct comparison of HC to the other treatment levels with multiple machines.

Techniques described in Section 4.2.2 for use in determining the separation efficiency of FS were used to track the change in the mass of VS.

Again, since management and machine were not found to have a significant effect on the change of VS mass, the mean of individual machine samples at each treatment level for a given sample event was used to determine the change in VS mass. Table 4.19 summarizes the VS mass data for the eleven sample events used to evaluate change in VS. Compared to FS, VS had one less sample event due to sample corruption during laboratory analysis. Using the daily mean of the VS mass for each sample location allowed for a direct comparison of HC to the other treatment levels with multiple machines.

Table 4.19: Daily volatile solids mass data – GMF

Treatment Level	Mean (kg/d)	Standard Deviation (kg/d)	Median (kg/d)	Count
SLDM	22,050	1,765	22,254	11
SMS	17,467	2,304	18,420	11
MINI	15,154	3,177	15,983	11
HC Overflow	12,765	1,960	13,418	11

Sand laden dairy manure provided the baseline mass of VS, which was used to determine the cumulative change in VS. Table 4.20 summarizes the mean percent change in the VS mass at each treatment level. The 95% confidence interval is also shown in Table 4.20.

Table 4.20: Cumulative change in volatile solids – GMF

Treatment Level	Mean (%)	95% Confidence Limits Lower (%)	Upper (%)
SMS	20	12	27
MINI	29	21	38
HC Overflow	42	36	48

Figure 4.6 graphically displays the cumulative VS change with the 95% confidence interval for the three levels of the SSS.

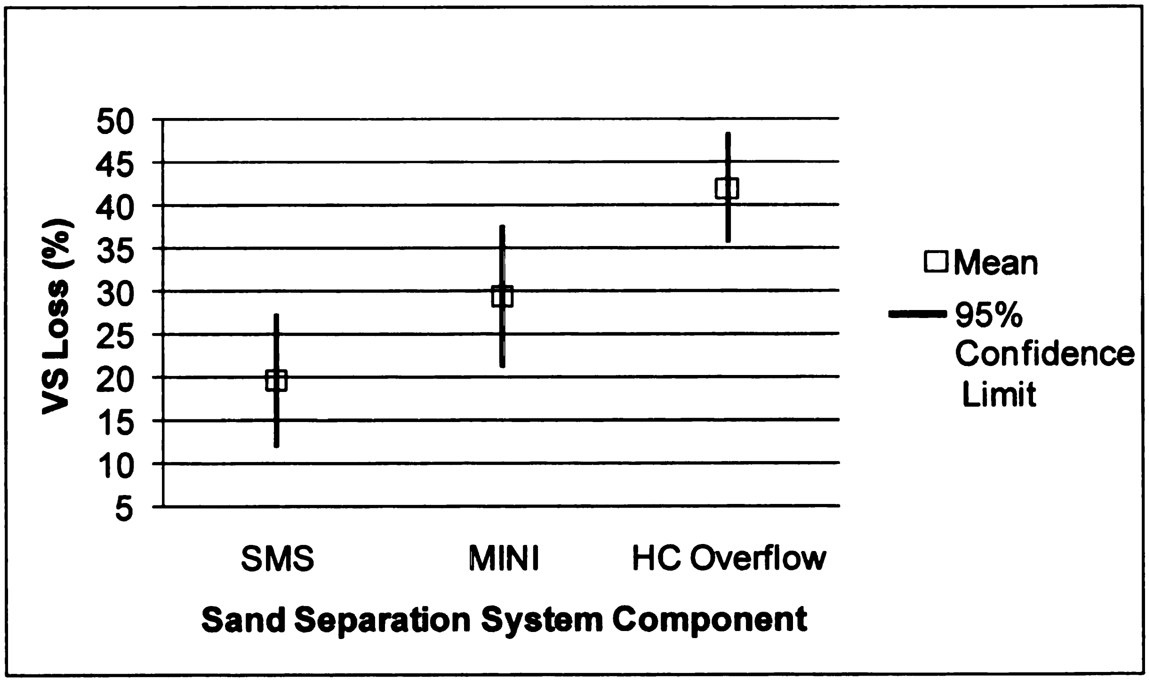

Figure 4.6: Cumulative change in volatile solids – GMF

The change in VS during sand separation is likely caused by the removal of VS with FS. Coarse material, sand, removed by the SMS and HC (underflow) had higher concentrations of VS compared to new sand, 3.3% and 4.2%

compared to 2.2%, respectively. Sand sample data is included in Appendix F. Samples from the MINI were not evaluated, as a representative sample of could not be collected.

Biodegradation of VS may have also contributed to the VS reduction. At multiple locations in the SSS, significant aeration could occur due to agitation and turbulence. Both short-term intense aeration and long-term low intensity aeration has been shown to lower chemical oxygen demand manure, an indicator of waste strength similar to VS, by as much as 60% (Classen and Liehr, 2005; Zhang et al., 1997).

Data in Table 4.21 compares the change in VS for each level of the SSS, constructed using the data set shown in Table 4.19. Similar to the cumulative change, treatment level changes were calculated using Equation 2.12. The VS mass of the component influent (effluent from the previous unit) was used instead of the VS mass of SLDM. Each level of the SSS saw similar changes in the mean VS mass remaining in the manure. Figure 4.7 depicts the mean and confidence interval for the VS change for each SSS treatment level.

Table 4.21: Treatment level change in volatile solids – GMF

Treatment Level		95% Confidence Limits	
	Mean (%)	Lower (%)	Upper (%)
SMS	20	12	27
MINI	13	5	21
HC Overflow	13	3	24

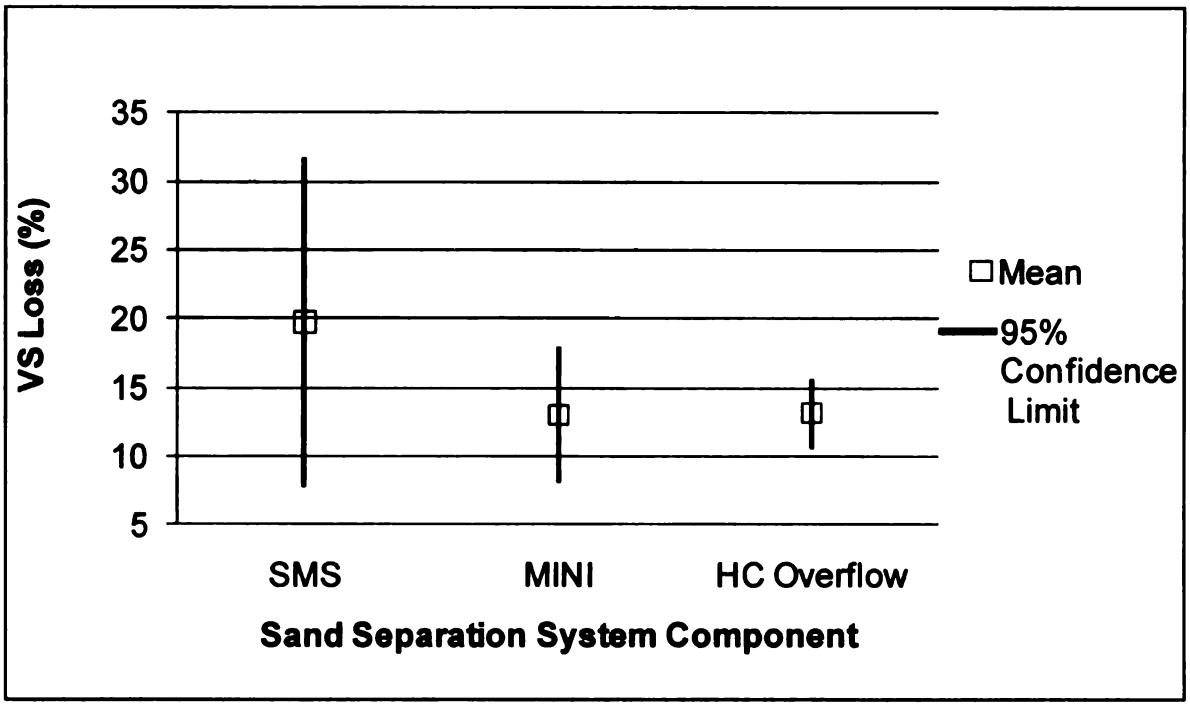

Figure 4.7: Treatment level change in volatile solids – GMF

Uncertainty or design imprecision is the uncontrolled stochastic variation in variable values (Antonsson, 2001). Based on the discussion in section 2.6.1, biogas production under both laboratory and field conditions is naturally uncertain. Utilizing site-specific data, such as a change in the mass VS due to sand separation observed at GMF, even if not statistically significant, provides system planners with information to help cope with the uncertainty of biogas production.

4.5 Impact of SSS on anaerobic digester design

Based on the data evaluated to determine the FS separation and change in the VS, it is obvious that SSS effluent has characteristics very different from that of SLDM. The addition of dilution water and changes in the mass of VS due to the operation of the SSS at GMF impact the amount of energy needed to heat the influent to the operating temperature of 35°C and the biogas potential.

4.5.1 Heating requirements of sand separation system effluent

Energy required to heat SLDM and the various SSS products from ambient temperature to the operating temperature of the AD, typically 35°C, was determined using Equation 2.19. Table 4.22 summarizes the requirements of SLDM and the SSS products at GMF over a range of ambient air temperatures. Manure mass flow rates from Table 4.9 were used for the predictions.

Table 4.22: Heating required achieve AD operating temperature – GMF

Ambient	Energy Required				
Temperature	Manure	SLDM	SMS	MINI	HC overflow
(°C)	(kJ/d)	(kJ/d)	(kJ/d)	(kJ/d)	(kJ/d)
0	28,934,420	30,647,565	73,836,251	67,123,865	61,021,695
5	24,800,932	26,269,342	63,288,215	57,534,741	52,304,310
10	20,667,443	21,891,118	52,740,179	47,945,618	43,586,925
15	16,533,955	17,512,894	42,192,143	38,356,494	34,869,540
20	12,400,466	13,134,671	31,644,108	28,767,371	26,152,155
25	8,266,977	8,756,447	21,096,072	19,178,247	17,434,770
30	4,133,489	4,378,224	10,548,036	9,589,124	8,717,385
35	0	0	0	0	0

Dilution water, added during SSS, approximately doubled the energy needed to raise the ambient temperature of SMS, MINI and HC overflow to the temperature. Increasing the need for energy to heat the AD influent (with an ambient temperature less than the operating temperature) results in less energy available for offset elsewhere on the farm or for sale as renewable energy, unless waste heat from a combined-heat and power biogas utilization system is available.

4.5.2 Biogas potential from sand separation products

The USDA (2007) indicated that digesters using dairy manure as a feedstock can produce approximately 1.9 m^3 of biogas/cow/day with an average energy content of 20,900 kJ/m^3 (NRCS, 2007). This is equivalent to 39,700 kJ/cow/day. Biogas production is the ultimate measure of economic viability of an AD and is based largely on the mass of VS entering the system daily, as evident by the above conversions. Sand bedding and the subsequent separation does statistically impact the mass of VS contained in the manure stream, as previously demonstrated.

Biogas and energy potential of the various sample locations at GMF, summarized in Tables 4.23 and 4.24, were predicted using Equations 2.14 and 2.15, which rely on the VS concentration of AD feedstock. Mean and standard deviation data from the daily average VS mass data presented in Table 4.19 was used to calculate the low (mean – standard deviation), high (mean + standard deviation and mean biogas potential in Table 4.23. A biogas yield of 0.27 m^3/kg VS was used to calculate the biogas potential. The biogas yield was the mean of literature values (U.S. Department of Agriculture (2007); Steffen et al., 1998; Morris, 1976), which ranged from 0.18 m^3/kg VS to 0.39 m^3/kg VS.

Table 4.23: Anaerobic digester biogas potential – GMF

Treatment Level	VS Mass	Biogas Yield		
		Low	Mean	High
	(kg/d)	(m^3/d)	(m^3/d)	(m^3/d)
SLDM	22,050	3,984	5,907	8,655
SMS	17,467	3,156	4,680	6,856
MINI	15,154	2,738	4,060	5,948
HC Overflow	12,765	2,307	3,420	5,011

The theoretical biogas yield values in Table 4.23 was determined using the mass of VS in the manure at each treatment level, Table 4.20. Table 4.23 indicates that on average, biogas potential was reduced by 42%, due to the change in the mass of VS in the manure during sand separation. Theoretical energy potential based on biogas potential is summarized in Table 4.24.

Table 4.24: Anaerobic digester energy potential – GMF

Treatment Level	Energy Potential		
	Low	Mean	High
	(kJ/d)	(kJ/d)	(kJ/d)
SLDM	80,060,494	118,710,388	173,924,522
SMS	63,419,254	94,035,445	137,772,861
MINI	55,021,966	81,584,294	119,530,478
HC Overflow	46,349,048	68,724,450	100,689,311

Comparing the energy potential of HC overflow as a AD feedstock (Table 4.24) to the energy needed to heat the influent (Table 4.22) indicates that biogas can produce sufficient energy to heat the influent from 0 to 35°C (Table 4.25).

Table 4.25: AD energy potential compared to heating requirement – GMF

Ambient Temperature	Energy potential required to heat influent, %			
(°C)	SLDM	SMS	MINI	HC Overflow
0	26	75	81	89
5	23	64	70	76
10	19	53	58	64
15	15	43	46	51
20	11	32	35	38
25	8	21	23	25
30	4	11	12	13
35	0	0	0	0

On average, HC overflow compared to SLDM required over three times the energy potential to achieve the target temperature. According to the theoretical data in Table 4.25, at freezing only 26% of the energy potential of SLDM was needed to heat the AD influent to the operating temperature compared to 89% of the HC overflow. Inefficiencies with direct combustion are between 65% and 85% (Wilkie, 2008), potential resulting in a negative energy balance for dilute influent feedstocks. Table 4.26 evaluates the energy balance assuming all biogas is used for heating, with an average combustion efficiency of 80%.

Table 4.26: AD energy potential compared to heating requirement assuming a combustion efficiency of 80% – GMF

Ambient Temperature	Energy potential required to heat influent assuming a combustion efficiency of 80%			
(°C)	SLDM	SMS	MINI	HC Overflow
0	32	98	111	111
5	28	84	95	95
10	23	70	79	79
15	18	56	63	63
20	14	42	48	48
25	9	28	32	32
30	5	14	16	16
35	0	0	0	0

Table 4.26 indicates that at 0°C, MINI and HC overflow cannot produce enough energy from biogas to support the heating needs of the influent. Due to the potential energy deficiency, alternative heat sources maybe required to maintain temperature during extreme cold. Alternative heat options included standby heat or waste heat recovery from AD effluent. In addition, maximizing biogas production, as shown in Tables 4.23 and 4.24 could increase energy yield by nearly 50%, eliminating energy deficient periods.

Waste heat recovered from an electrical generator (combined heat and power unit) using biogas as its fuel is commonly used to heat anaerobic digesters. Assuming that 40% of the biogas energy potential is recoverable as waste heat through the cooling of the engine and exhaust, Table 4.27 was generated to demonstrate the percent of the heat required that could be provided by waste heat. Sand laden dairy manure has the potential to generate sufficient waste heat from combined heat and power to maintain the AD operating temperature at ambient temperature of 0°C. In comparison, the AD heat requirement could only be supported by waste heat from the SMS, MINI and HC overflow to an ambient temperature of 20°C.

Table 4.27: Anaerobic digester heating requirement from waste heat – GMF

Ambient Temperature	Waste heat required to maintain AD operating temperature, %[1]			
(°C)	SLDM	SMS	MINI	HC Overflow
0	66			
5	56			
10	47			
15	38			
20	28	80	87	96
25	19	53	58	64
30	9	27	29	32
35	0	0	0	0

[1]Assuming a 40% heat recovery efficiency of the total biogas energy potential

In addition to the heat energy balance, the loss of energy revenue due to a decreased amount of VS is critical to the economic viability of AD systems. Table 4.28 summarizes the annual electrical energy potential from biogas produced by an AD system using manure from the different sample locations available at GMF. Table 4.28 is based on the mean mass of VS shown in Table 4.19. The change in VS during sand separation amounted to a reduction of approximately $128,000 in electrical revenue when comparing SLDM to HC overflow.

Table 4.28: Electrical generation potential of SSS products – GMF

AD Influent Source	Mean	
	Electrical Potential (kWh/yr)*	Electrical Revenue (yr)**
SLDM	3,791,313	$303,305
SMS	3,003,257	$240,261
MINI	2,605,598	$208,448
HC Overflow	2,194,887	$175,591
*Assuming 35% flywheel efficiency and 90% on-time efficiency		
**Assumes electrical value of $0.08 per kWh		

Utilizing the data in Table 4.28, along with FS separation efficiency and residual particle size data, system planners can value engineer the integration of sand separation and AD systems. Economic and risk factors should be considered when balancing between the level of sand separation, mixing costs, the risk of sedimentation and impacts on biogas potential for new systems. Similar, at existing facilities, an economic evaluation can provide guidance for the allocation of funds for improving or abandoning SSS components. An example of this is in regards to the operation of the MINI pits at GMF. Early in the AD project, the MINI's were identified as a cause of lost VS, however due to a management decision, the MINI's were not abandoned. A system wide economic evaluation may have provided different guidance to the management.

4.5.3 Verification of energy analyses

Actual operational data from the electrical generator at GMF allowed for the verification of the energy analyses presented previously. Table 4.29 contains electrical generation data using HC overflow as the AD feedstock from GMF.

Table 4.29: Operational data from the electrical generator – GMF

Year	Month	Electrical production				Generator Size
		MWh/month	kWh/month	kWh/d	kWh/yr[2]	kW
2008	March	108	107,590	3,471	1,266,785	145
	April	81	80,825	2,694	983,371	112
	May	110	110,221	3,556	1,297,763	148
	June	50	49,801	1,660	605,912	69
	July	171	170,669	5,505	2,009,490	229
	August	65	64,501	2,081	759,447	87
	September	24	23,806	794	289,640	33
	October	15	15,497	500	182,465	21
	November	58	57,960	1,932	705,180	81
	December	57	56,860	1,834	669,481	76
2009 [3]	January	129	129,443	4,176	1,524,087	174
	February	235	235,331	8,405	3,067,708	350
	March	318	318,369	10,270	3,748,538	428
2008 mean		74	73,773	2,403	876,953	100
2009 mean		228	227,714	7,617	2,780,111	317
Overall mean		109	109,298	3,606	1,316,144	150

[1]Provided by North American Biofuels (Marvin, 2009)

[2]Extrapolation of monthly electrical production to annual value

[3]Starting in mid-January 2009, 240,000 lb/week of ethanol syrup was added to the AD influent

The digester at GMF began receiving manure in July of 2007, but the biogas utilization system, an 800 kW electrical generation, did not become operational until March of 2008. Electrical production during 2008 was highly variable due to common startup issues. Generation peaked in July of 2008 when 170,669 kWh were produced for the month, equivalent to an annual electrical output of 2.01 million kWh/yr. Comparing the actual peak electrical output of the AD system at GMF to the theoretical electrical potential of the HC overflow, shown in Table 4.28, the actual operating system achieved 92% of the predicted potential. The basis for Table 4.28 is the estimated mean mass of VS contained in Table 4.19.

The combination of an electrical storm in August and the mixer failure in September 2008 negatively impacted biogas production and electrical generation for the remainder of 2008. By January of 2009, the system was restored to full capacity and operating at the target temperature of 35°C.

To improve biogas production, condensed distillers soluble (syrup) from ethanol production was added to the digester feedstock beginning in January of 2009. The target addition of syrup was 109,000 kg/week, but the actual mass and timing of addition varied week to week. Based on the data in Table 4.28, it is clear that the addition of syrup resulted in increased biogas production.

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 Summary

The objectives of the research were to quantify separation efficiency of the sand separation system, evaluate the particle size distribution of residual sand in the manure stream to determine the potential for accumulation in the AD tanks, predict the loss of volatile solids during sand separation and determine the design implication of sand separation on anaerobic digester.

Quantification of sand separation efficiency was attempted using traditional mass balance, however the unstable flow rate of several inputs and outputs from a simple SSS did not produce results within the target closure of ±10%. To address difficulties with the traditional mass balance, a semi-empirical mass balance technique was developed to evaluate the separation efficiency of a complex SSS with multiple units and treatment levels, similar to GMF. This technique used a combination of industry standards and farm-specific data to predict daily manure production, bedding usage and manure and solids flow rates throughout a sand separation system. For the semi-empirical mass balance the effluent flow rate of the system, at a minimum, should be measured on a daily basis. In addition, samples should be collected and evaluated to determine the solids concentration of the effluent from each step of the SSS. Usage of industry standard data was limited to predicting the baseline mass of manure and bedding generated by the dairy cows on a daily basis. The manure and solids flow information was used to predict the FS separation efficiency of the SSS, in addition to the change in VS resulting from the removal of FS. Mean cumulative FS separation efficiency of the SSS was found to be 97% with a 95% confidence interval of 96% to 98%. Sand manure separation accounted for the majority of the FS separation, with a confidence interval of 83% to 90%.

Effectiveness of the semi-empirical mass balance compared to the traditional mass balance was improved by using measured daily flow rates and a standardized data set to predict baseline flow rates for which direct measurement is not practical. While direct flow rate measurement is desirable and would reduce variability, safety and cost often are prohibitive on commercial operations. Thus, the semi-empirical mass balance provides a cost effective and efficient method for qualitatively determining the separation efficiency on a variety of commercial dairy farms.

For planning and design purposes, understanding the change in particle size of new sand compared to residual sand provides the basis for predicting scour velocity and sizing mixing systems. The mean particle size of the residual sand was 0.195 mm compared to the average particle size of new sand, 0.69 mm. During system maintenance, one of the anaerobic digester tanks was emptied after approximately fifteen months of operation, inspection of the tank floor indicated that only 25 to 50 mm of sludge (sand and manure) had accumulated, verifying the modeling technique. Theoretical mixing power required to initiate and completely scour residual sand entering the anaerobic digester was determined using the mean particle size of the residual sand. The mixing system installed and operating in the anaerobic digester at GMF has sufficient power to achieve complete scour of the mean sand particle remaining in the manure used as feedstock. Consequently, the model and verification steps result in a conclusion that the SSS is adequate to prevent AD system operating difficulties.

Sand separation does, however, come with a cost in regards to downstream treatment. Dilution water added during the sand separation process more than doubled the energy needed to heat the HC overflow to the target operating temperature. Further, the change in the VS mass throughout the SSS reduced the theoretical biogas potential of the system effluent compared to SLDM. The treatment effect of the SSS on mass VS in manure was not found to be statistically significant. However, system planners should be aware of potential changes in biogas production due to changes in VS mass.

5.2 General conclusions

Major research findings from the research are summarized below.

1. Quantifying sand separation efficiency using mass balance was not effective due to large operational variations over the sample collection interval. However, a semi-empirical mass balance approach was developed to provide an effective method for acquiring necessary FS separation efficiency design information over a wide range of dynamic commercial SSS. Using the semi-empirical approach, treatment was found to have a statistically significant effect on the change in FS mass

throughout the SSS, resulting in a FS separation efficiency confidence interval (95%) of 96% to 98%.

2. Residual sand particles found in the sand separation system effluent and sludge of downstream units had a mean diameter of 0.195 mm compared to new sand which had a mean diameter of 0.69 m. This resulted in greater than a 50% decrease in the mean scour velocity. Observational measurements confirmed theoretical prediction, that the propeller mixing system used in the AD at GMF (case study farm) achieved the scour velocity of the mean residual sand particle size.
3. While not found to have produced statistically significant results on the case study farm, the semi-empirical mass balance approach applied to track changes in the mass of VS remaining in the manure after sand separation, provided valuable information to system planners coping with uncertain biogas production potential.
4. Sand separation can remove sufficient sand to minimize negative impacts on AD, however the addition of dilution water and the potential loss of VS could potentially reduce the amount of biogas-derived energy available for use elsewhere on the farm or as a salable product. System planners need to consider changes in the AD feedstock due to sand separation when selection heating and biogas utilization equipment.

CHAPTER 6: RECOMMENDATIONS FOR FUTURE WORK

The following recommendations are made with respect to areas that need further research.

1. Evaluate deleterious effect on microbial activity or biogas production during anaerobic digestion of manure containing sand bedding or residual sand. Compare other AD system to see if any common problems exist other than the addition of dilution water and the reduced mass of VS.
2. Investigate methods for improving biogas production from AD systems using dilute materials as feedstocks. Included is the development of hybrid systems that combine existing technologies for treating both high and low solids feedstocks. Also, bolt on technologies such as solid-liquid separation and membrane filters could be used to decouple the solid and liquid retention times, thus increasing the residence time of the organic matter in the AD.
3. Investigate methods for improving the heat energy balance for systems using dilute feedstock by exchanging heat from the digester effluent with the cooler influent. Based on experiences at GMF, the use of traditional shell and tube heat exchangers for recovering waste heat from the digester effluent may be impractical due to clogging caused by the buildup of scale containing animal hair, organic matter and crystalline formations believed to be struvite.

4. Explore the usefulness of computer-based models to optimize the digester mixing system design to effectively control sedimentation, reduce low velocity (dead) zones while maximizing biogas production. Computational fluid dynamic software could be used to model and optimize anaerobic digester mixing for the feedstock characteristics.
5. Alternative uses of biogas should be evaluated to improve the revenue potential of AD systems. Such alternatives may include operation of the combined heat and power unit as a peak demand plants to maximize electrical revenue or biogas upgrading to natural gas standards and storage for on farm heating during cooler periods or as transportation fuel in short range vehicles.

APPENDIX A

MDF Solids Data

Table A1: Solids concentration data, MDF

Sample ID	Sample Date	Moisture (%)	TS (%)	FS (%)	VS (%)
FAN effluent	06/27/06	95.2	4.83	1.72	3.11
HC underflow	06/27/06	93.0	7.03	2.54	4.49
Manure	06/27/06	83.8	16.18	1.94	14.23
Reclaimed sand	06/27/06	8.7	91.27	89.23	2.04
SLDM	06/27/06	79.6	20.38	12.01	8.36
SMS	06/27/06	93.8	6.20	2.49	3.70
FAN effluent	07/12/06	97.3	2.72	0.83	1.89
HC underflow	07/12/06	97.5	2.50	0.74	1.76
Manure	07/12/06	81.7	18.27	3.23	15.04
New sand	07/12/06	17.65	82.35	78.66	3.69
New sand	07/12/06	5.05	94.95	93.73	1.22
SLDM	07/12/06	95.9	4.14	0.92	3.23
SMS	07/12/06	97.5	2.54	0.78	1.76
FAN effluent	12/18/06	94.73	5.27	2.25	3.02
HC underflow	12/18/06	93.57	6.43	2.85	3.58
Manure	12/18/06	82.31	17.69	2.51	15.18
Reclaimed sand	12/18/06	14.26	85.74	84.32	1.42
SLDM	12/18/06	82.68	17.32	9.08	8.24
SMS	12/18/06	92.61	7.39	3.74	3.64
FAN effluent	12/21/06	96.29	3.71	1.36	2.35
HC underflow	12/21/06	95.61	4.39	1.54	2.85
Manure	12/21/06	83.47	16.53	3.04	13.49
Reclaimed sand	12/21/06	8.66	91.34	89.41	1.93
SLDM	12/21/06	84.43	15.57	8.40	7.17
SMS	12/21/06	94.32	5.68	2.60	3.08
FAN effluent	01/03/07	96.24	3.76	1.25	2.51

Table A1: Solids concentration data, MDF continued

HC underflow	01/03/07	96.47	3.53	1.04	2.49
Manure	01/03/07	82.64	17.36	2.44	14.93
Reclaimed sand	01/03/07	7.55	92.45	90.65	1.80
SLDM	01/03/07	76.36	23.64	14.20	9.44
SMS	01/03/07	95.10	4.90	1.85	3.05
FRESH H2O	03/09/07	99.91	0.09	-0.04	0.12
HC overflow	03/09/07	96.09	3.91	1.07	2.83
HC underflow	03/09/07	46.83	53.17	50.42	2.75
HC underflow	03/09/07	66.50	33.50	31.82	1.68
Recycle H2O	03/09/07	95.84	4.16	1.39	2.77
Reclaimed sand	03/09/07	34.34	65.66	64.56	1.10
Reclaimed sand	03/09/07	71.51	28.49	27.29	1.20
SLDM	03/09/07	86.55	13.45	7.56	5.89
SLDM	03/09/07	85.00	15.00	9.26	5.74
SMS	03/09/07	95.94	4.06	1.63	2.43
SMS	03/09/07	96.94	3.06	1.01	2.05
FRESH H2O	03/16/07	99.88	0.12	0.11	0.01
FRESH H2O	03/16/07	99.74	0.26	0.24	0.02
FRESH H2O	03/16/07	99.92	0.08	0.04	0.04
FRESH H2O	03/16/07	99.96	0.04	0.03	0.02
HC overflow	03/16/07	96.89	3.11	0.86	2.26
HC overflow	03/16/07	95.30	4.70	1.29	3.41
HC overflow	03/16/07	91.25	8.75	4.21	4.54
HC overflow	03/16/07	97.95	2.05	0.69	1.36
HC overflow	03/16/07	95.35	4.65	1.34	3.31
HC overflow	03/16/07	93.67	6.33	2.32	4.01
HC underflow	03/16/07	64.17	35.83	34.07	1.75
Recycle H2O	03/16/07	95.73	4.27	1.66	2.61
RecycleH2O	03/16/07	95.78	4.22	1.68	2.55
Recycle H2O	03/16/07	95.60	4.40	1.68	2.72
Recycle H2O	03/16/07	95.46	4.54	1.84	2.70
Reclaimed sand	03/16/07	18.25	81.75	78.25	3.49
Reclaimed sand	03/16/07	43.87	56.13	54.98	1.15

Table A1: Solids concentration data, MDF continued

Reclaimed sand	03/16/07	18.37	81.63	78.86	2.77
Reclaimed sand	03/16/07	16.48	83.52	80.32	3.20
Reclaimed sand	03/16/07	18.90	81.10	79.59	1.51
SLDM	03/16/07	97.44	2.56	1.36	1.20
SLDM	03/16/07	74.92	25.08	16.94	8.14
SLDM	03/16/07	67.74	32.26	23.38	8.87
SLDM	03/16/07	89.34	10.66	7.50	3.16
SMS	03/16/07	97.60	2.40	0.54	1.86
SMS	03/16/07	90.62	9.38	5.30	4.08
SMS	03/16/07	97.02	2.98	0.76	2.22
SMS	03/16/07	91.93	8.07	3.79	4.28
FRESH H2O	05/16/07	99.92	0.08	0.05	0.03
FRESH H2O	05/16/07	99.90	0.10	0.04	0.06
HC overflow	05/16/07	95.97	4.03	1.15	2.88
HC overflow	05/16/07	95.89	4.11	1.22	2.89
HC underflow	05/16/07	38.50	61.50	59.83	1.67
HC underflow	05/16/07	36.29	63.71	59.65	4.06
Recycle H2O	05/16/07	95.68	4.32	1.47	2.85
Recycle H2O	05/16/07	96.11	3.89	1.14	2.75
Reclaimed sand	05/16/07	31.31	68.69	65.16	3.53
Reclaimed sand	05/16/07	27.46	72.54	68.47	4.07
SLDM	05/16/07	72.15	27.85	18.34	9.51
SLDM	05/16/07	70.48	29.52	20.89	8.63
SMS	05/16/07	96.07	3.93	3.02	0.91
SMS	05/16/07	96.46	3.54	1.04	2.50
HC underflow	05/31/07	43.75	56.25	48.16	8.09
New sand	05/31/07	2.11	97.89	95.85	2.04
Reclaimed sand	05/31/07	18.24	81.76	79.66	2.10
SLDM	05/31/07	70.84	29.16	19.08	10.08
SMS	05/31/07	96.35	3.65	1.05	2.60

Table A2: TS concentration data, MDF

Sample Location	Mean TS (%)	Standard Deviation (%)	Coefficient of Variation (%)	Median (%)	Number of Samples
Manure	15.2	5.0	33.2	16.9	6
SLDM	19.0	9.4	49.4	18.8	14
SMS	4.8	2.2	45.3	4.0	14
HC Overflow	4.7	1.9	39.7	4.3	14

Table A3: FS concentration data, MDF

Sample Location	Mean FS (%)	Standard Deviation (%)	Coefficient of Variation (%)	Median (%)	Number of Samples
Manure	3.0	1.1	35.3	2.8	6
SLDM	12.1	7.0	57.8	10.6	14
SMS	2.1	1.4	67.8	1.7	14
HC Overflow	1.6	1.0	61.2	1.3	14

Table A4: VS concentration data, MDF

Sample Location	Mean VS (%)	Standard Deviation (%)	Coefficient of Variation (%)	Median (%)	Number of Samples
Manure	13.0	4.0	30.5	14.6	6
SLDM	7.0	2.7	39.4	8.2	14
SMS	2.7	1.0	35.4	2.6	14
HC Overflow	3.0	0.9	30.6	2.9	14

APPENDIX B

GMF Solids Data

Table B1: Solids concentration data from, GMF

Sample ID	Sample Location	Herd Management	Sample Date	Moisture (%)	TS (%)	FS (%)	VS (%)
Manure	Farm 3 SMS 5	Special Needs	05/09/06	83.5	16.48	5.14	11.34
MINI	Farm 3 SMS 5	Special Needs	05/09/06	96.7	3.28	1.10	2.18
SLDM	Farm 3 SMS 5	Special Needs	05/09/06	80.0	19.98	11.27	8.71
SMS	Farm 3 SMS 5	Special Needs	05/09/06	96.2	3.82	1.31	2.51
Manure	Farm 3 SMS 5	Special Needs	05/15/06	83.7	16.29	2.50	13.79
MINI	Farm 3 SMS 5	Special Needs	05/15/06	96.4	3.63	1.10	2.53
SLDM	Farm 3 SMS 5	Special Needs	05/15/06				
SMS	Farm 3 SMS 5	Special Needs	05/15/06	95.8	4.23	1.33	2.89
Manure	Farm 2 SMS 4	Lactating	05/17/06	86.6	13.36	2.32	11.04
MINI	Farm 2 SMS 4	Lactating	05/17/06	95.0	5.03	1.44	3.59
SLDM	Farm 2 SMS 4	Lactating	05/17/06	72.3	27.71	19.25	8.46
SMS	Farm 2 SMS 4	Lactating	05/17/06	94.0	5.96	2.03	3.93
Manure	Farm 2 SMS 3	Lactating	05/19/06	86.8	13.21	1.13	12.08
MINI	Farm 2 SMS 3	Lactating	05/19/06	95.1	4.94	1.38	3.55
SLDM	Farm 2 SMS 3	Lactating	05/19/06	76.3	23.73	15.80	7.93
SMS	Farm 2 SMS 3	Lactating	05/19/06	94.5	5.51	1.84	3.67
Manure	Farm 2 SMS 3	Lactating	05/22/06	87.2	12.80	1.32	11.48
Manure	Farm 3 SMS 5	Special Needs	05/22/06	86.5	13.47	1.64	11.83
Manure	Farm 3 SMS 6	Special Needs	05/22/06	87.3	12.67	1.70	10.97
MINI	Farm 2 SMS 3	Lactating	05/22/06	95.4	4.58	1.25	3.32
MINI	Farm 3 SMS 5	Special Needs	05/22/06	94.4	5.61	1.79	3.82
MINI	Farm 3 SMS 6	Special Needs	05/22/06	91.2	8.82	2.28	6.54
SLDM	Farm 2 SMS 3	Lactating	05/22/06	71.9	28.10	19.21	8.89
SLDM	Farm 3 SMS 5	Special Needs	05/22/06	71.1	28.86	20.86	8.00
SLDM	Farm 3 SMS 6	Special Needs	05/22/06	72.5	27.54	18.85	8.69
SMS	Farm 2 SMS 3	Lactating	05/22/06	94.2	5.77	2.05	3.72
SMS	Farm 3 SMS 5	Special Needs	05/22/06	93.8	6.18	2.48	3.69
SMS	Farm 3 SMS 6	Special Needs	05/22/06	95.2	4.76	1.71	3.06
Manure	Farm 2 SMS 2	Lactating	05/26/06	86.7	13.34	1.52	11.82
Manure	Farm 2 SMS 3	Lactating	05/26/06	87.0	13.01	1.38	11.64
Manure	Farm 2 SMS 4	Lactating	05/26/06	87.9	12.11	1.46	10.65
Manure	Farm 3 SMS 5	Special Needs	05/26/06	82.8	17.22	4.81	12.41
Manure	Farm 3 SMS 6	Special Needs	05/26/06	85.1	14.91	1.88	13.03

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Table B1: Solids concentration data from, GMF continued

MINI	Farm 2 SMS 2	Lactating	05/26/06	95.7	4.32	1.08	3.23
MINI	Farm 2 SMS 3	Lactating	05/26/06	95.7	4.32	1.26	3.06
MINI	Farm 2 SMS 4	Lactating	05/26/06	96.8	3.17	0.88	2.28
MINI	Farm 3 SMS 5	Special Needs	05/26/06	98.2	1.83	0.69	1.14
MINI	Farm 3 SMS 6	Special Needs	05/26/06	93.8	6.23	2.22	4.01
SLDM	Farm 2 SMS 2	Lactating	05/26/06	83.4	16.56	8.53	8.04
SLDM	Farm 2 SMS 3	Lactating	05/26/06	71.4	28.62	20.43	8.20
SLDM	Farm 2 SMS 4	Lactating	05/26/06	70.1	29.86	25.32	4.54
SLDM	Farm 3 SMS 6	Special Needs	05/26/06	90.1	9.86	4.74	5.11
Manure	Farm 2 SMS 1	Lactating	06/02/06	86.7	13.30	1.35	11.94
Manure	Farm 2 SMS 2	Lactating	06/02/06	85.5	14.51	1.65	12.86
Manure	Farm 2 SMS 3	Lactating	06/02/06	86.0	13.96	1.29	12.66
Manure	Farm 2 SMS 4	Lactating	06/02/06	87.0	12.99	1.29	11.69
Manure	Farm 3 SMS 5	Special Needs	06/02/06	85.6	14.38		
Manure	Farm 3 SMS 6	Special Needs	06/02/06	85.9	14.11	1.39	12.72
MINI	Farm 2 SMS 1	Lactating	06/02/06	94.9	5.10	1.38	3.72
MINI	Farm 2 SMS 2	Lactating	06/02/06	97.1	2.95	0.94	2.01
MINI	Farm 2 SMS 3	Lactating	06/02/06	93.4	6.59	1.93	4.66
MINI	Farm 2 SMS 4	Lactating	06/02/06	93.8	6.19	1.45	4.75
MINI	Farm 3 SMS 5	Special Needs	06/02/06	95.3	4.74	1.29	3.44
SLDM	Farm 2 SMS 1	Lactating	06/02/06	55.5	44.54	35.32	9.22
SLDM	Farm 2 SMS 2	Lactating	06/02/06	90.3	9.74	3.92	5.82
SLDM	Farm 2 SMS 3	Lactating	06/02/06	67.4	32.58	23.97	8.60
SLDM	Farm 2 SMS 4	Lactating	06/02/06	62.6	37.42	28.45	8.97
SLDM	Farm 3 SMS 5	Special Needs	06/02/06	74.8	25.21	16.74	8.48
Manure	Farm 2 SMS 3	Lactating	06/16/06	87.1	12.87	1.45	11.41
Manure	Farm 2 SMS 4	Lactating	06/16/06	87.7	12.27	1.22	11.06
Manure	Farm 3 SMS 5	Special Needs	06/16/06	85.0	14.99	1.99	13.01
Manure	Farm 3 SMS 6	Special Needs	06/16/06	94.4	5.59	1.90	3.69
MINI	Farm 2 SMS 3	Lactating	06/16/06	95.2	4.79	1.43	3.37
MINI	Farm 2 SMS 4	Lactating	06/16/06	95.6	4.42	1.16	3.26
MINI	Farm 3 SMS 5	Special Needs	06/16/06	97.3	2.67	1.05	1.62
MINI	Farm 3 SMS 6	Special Needs	06/16/06	94.3	5.69	1.79	3.90
SLDM	Farm 2 SMS 3	Lactating	06/16/06	69.6	30.36	21.85	8.51
SLDM	Farm 2 SMS 4	Lactating	06/16/06	60.2	39.82	31.61	8.21
SLDM	Farm 3 SMS 5	Special Needs	06/16/06	50.2	49.83	42.32	7.51
SLDM	Farm 3 SMS 6	Special Needs	06/16/06	89.2	10.80	6.67	4.12
Manure	Farm 2 SMS 1	Lactating	06/20/06	83.2	16.83	1.94	14.89

Table B1: Solids concentration data from, GMF continued

Manure	Farm 2 SMS 2	Lactating	06/20/06	81.0	19.04	4.72	14.32
Manure	Farm 2 SMS 3	Lactating	06/20/06	85.7	14.28	1.88	12.39
Manure	Farm 2 SMS 4	Lactating	06/20/06	87.0	13.03	1.53	11.50
Manure	Farm 3 SMS 5	Special Needs	06/20/06	80.9	19.06	1.47	17.60
Manure	Farm 3 SMS 6	Special Needs	06/20/06	85.2	14.84	2.11	12.73
MINI	Farm 2 SMS 1	Lactating	06/20/06	92.6	7.39	2.18	5.22
MINI	Farm 2 SMS 2	Lactating	06/20/06	95.1	4.87	1.26	3.61
MINI	Farm 2 SMS 3	Lactating	06/20/06	95.1	4.89	1.53	3.35
MINI	Farm 2 SMS 4	Lactating	06/20/06	94.6	5.37	1.46	3.91
MINI	Farm 3 SMS 5	Special Needs	06/20/06	96.0	4.02	1.40	2.63
MINI	Farm 3 SMS 6	Special Needs	06/20/06	94.5	5.54	1.87	3.68
SLDM	Farm 2 SMS 1	Lactating	06/20/06	69.7	30.26	20.89	9.38
SLDM	Farm 2 SMS 2	Lactating	06/20/06	75.3	24.70	15.33	9.37
SLDM	Farm 2 SMS 3	Lactating	06/20/06	55.6	44.41	36.18	8.23
SLDM	Farm 2 SMS 4	Lactating	06/20/06	69.6	30.37	21.59	8.78
SLDM	Farm 3 SMS 5	Special Needs	06/20/06	67.0	32.95	24.40	8.55
SLDM	Farm 3 SMS 6	Special Needs	06/20/06	89.6	10.45	5.30	5.14
SMS	Farm 2 SMS 1	Lactating	06/20/06	93.5	6.49	0.85	5.64
SMS	Farm 2 SMS 2	Lactating	06/20/06	93.2	6.82	2.25	4.57
SMS	Farm 2 SMS 3	Lactating	06/20/06	96.1	3.95	1.50	2.45
SMS	Farm 2 SMS 4	Lactating	06/20/06	94.0	5.98	2.18	3.80
SMS	Farm 3 SMS 5	Special Needs	06/20/06	95.3	4.66	1.72	2.94
SMS	Farm 3 SMS 6	Special Needs	06/20/06	94.7	5.33	1.87	3.46
Manure	Farm 2 SMS 1	Lactating	06/29/06	84.2	15.81	1.72	14.09
Manure	Farm 2 SMS 2	Lactating	06/29/06	85.1	14.94		
Manure	Farm 2 SMS 3	Lactating	06/29/06	86.3	13.73	1.50	12.23
Manure	Farm 2 SMS 4	Lactating	06/29/06	86.3	13.74	1.35	12.39
Manure	Farm 3 SMS 5	Special Needs	06/29/06	84.1	15.90	2.51	13.40
Manure	Farm 3 SMS 6	Special Needs	06/29/06	84.5	15.52	2.00	13.52
MINI	Farm 2 SMS 1	Lactating	06/29/06	94.2	5.82	1.76	4.07
MINI	Farm 2 SMS 2	Lactating	06/29/06	94.2	5.79	1.63	4.16
MINI	Farm 2 SMS 3	Lactating	06/29/06	94.5	5.47	1.47	3.99
MINI	Farm 2 SMS 4	Lactating	06/29/06	94.6	5.45	1.64	3.80
MINI	Farm 3 SMS 5	Special Needs	06/29/06	95.2	4.83	1.46	3.37
MINI	Farm 3 SMS 6	Special Needs	06/29/06	94.7	5.29	0.89	4.40
SLDM	Farm 2 SMS 2	Lactating	06/29/06	68.3	31.66	23.40	8.27
SLDM	Farm 2 SMS 3	Lactating	06/29/06	64.6	35.38	27.13	8.25
SLDM	Farm 2 SMS 4	Lactating	06/29/06	57.2	42.83	34.40	8.43
SLDM	Farm 3 SMS 5	Special Needs	06/29/06	76.4	23.57	15.14	8.42

Table B1: Solids concentration data from, GMF continued

SLDM	Farm 3 SMS 6	Special Needs	06/29/06	88.9	11.06	5.95	5.11
SMS	Farm 2 SMS 1	Lactating	06/29/06				
SMS	Farm 2 SMS 2	Lactating	06/29/06	92.4	7.62	3.00	4.62
SMS	Farm 2 SMS 3	Lactating	06/29/06	93.7	6.31	2.16	4.15
SMS	Farm 2 SMS 4	Lactating	06/29/06	94.1	5.90	2.22	3.68
SMS	Farm 3 SMS 5	Special Needs	06/29/06	96.7	3.28	1.28	2.00
SMS	Farm 3 SMS 6	Special Needs	06/29/06	92.8	7.20	3.08	4.12
Manure	Farm 2 SMS 1	Lactating	07/03/06	85.7	14.29	1.88	12.41
Manure	Farm 2 SMS 2	Lactating	07/03/06	86.5	13.49	2.24	11.25
Manure	Farm 2 SMS 3	Lactating	07/03/06	86.4	13.61	1.41	12.21
Manure	Farm 2 SMS 4	Lactating	07/03/06	84.4	15.55	2.50	13.06
Manure	Farm 3 SMS 5	Special Needs	07/03/06	84.1	15.89	3.32	12.57
Manure	Farm 3 SMS 6	Special Needs	07/03/06	85.0	15.02	2.68	12.34
MINI	Farm 2 SMS 1	Lactating	07/03/06	93.9	6.07	1.80	4.27
MINI	Farm 2 SMS 2	Lactating	07/03/06	93.5	6.47	2.01	4.46
MINI	Farm 2 SMS 3	Lactating	07/03/06	95.2	4.84	1.35	3.49
MINI	Farm 2 SMS 4	Lactating	07/03/06	94.7	5.31	1.64	3.67
MINI	Farm 3 SMS 5	Special Needs	07/03/06	97.2	2.79	1.15	1.63
MINI	Farm 3 SMS 6	Special Needs	07/03/06	94.7	5.27	1.88	3.39
SLDM	Farm 2 SMS 1	Lactating	07/03/06	69.4	30.57	22.53	8.04
SLDM	Farm 2 SMS 2	Lactating	07/03/06	69.6	30.43	22.06	8.37
SLDM	Farm 2 SMS 3	Lactating	07/03/06	63.3	36.72	28.17	8.55
SLDM	Farm 2 SMS 4	Lactating	07/03/06	64.9	35.11	27.10	8.01
SLDM	Farm 3 SMS 5	Special Needs	07/03/06	66.5	33.53	25.86	7.67
SLDM	Farm 3 SMS 6	Special Needs	07/03/06	95.3	4.66	1.88	2.79
SMS	Farm 2 SMS 1	Lactating	07/03/06	92.1	7.87	3.20	4.66
SMS	Farm 2 SMS 2	Lactating	07/03/06	91.4	8.59	3.94	4.65
SMS	Farm 2 SMS 3	Lactating	07/03/06	93.2	6.78	2.74	4.04
SMS	Farm 2 SMS 4	Lactating	07/03/06	93.3	6.67	2.76	3.90
SMS	Farm 3 SMS 5	Special Needs	07/03/06	97.2	2.79	1.17	1.63
SMS	Farm 3 SMS 6	Special Needs	07/03/06	93.4	6.64	2.80	3.83
Manure	Farm 2 SMS 1	Lactating	07/05/06	86.1	13.85	1.84	12.01
Manure	Farm 2 SMS 2	Lactating	07/05/06	83.5	16.55	1.93	14.61
Manure	Farm 2 SMS 3	Lactating	07/05/06	86.4	13.65	1.38	12.27
Manure	Farm 2 SMS 4	Lactating	07/05/06	81.4	18.60	7.62	10.99
Manure	Farm 3 SMS 5	Special Needs	07/05/06	79.2	20.79	6.74	14.05
Manure	Farm 3 SMS 6	Special Needs	07/05/06	85.1	14.95	2.55	12.40
MINI	Farm 2 SMS 1	Lactating	07/05/06	95.0	5.03	1.42	3.61
MINI	Farm 2 SMS 2	Lactating	07/05/06	95.0	4.99	1.32	3.67
MINI	Farm 2 SMS 3	Lactating	07/05/06	95.7	4.35	1.31	3.03
MINI	Farm 2 SMS 4	Lactating	07/05/06	96.2	3.77	1.09	2.68
MINI	Farm 3 SMS 5	Special Needs	07/05/06	94.8	5.22	1.53	3.69
MINI	Farm 3 SMS 6	Special Needs	07/05/06	97.5	2.55	0.80	1.75

Table B1: Solids concentration data from, GMF continued

SLDM	Farm 2 SMS 1	Lactating	07/05/06	66.1	33.86	25.54	8.32
SLDM	Farm 2 SMS 2	Lactating	07/05/06	63.8	36.24	28.00	8.24
SLDM	Farm 2 SMS 3	Lactating	07/05/06	61.4	38.63	30.80	7.83
SLDM	Farm 2 SMS 4	Lactating	07/05/06	59.5	40.51	33.15	7.36
SLDM	Farm 3 SMS 5	Special Needs	07/05/06	63.7	36.32	27.48	8.84
SLDM	Farm 3 SMS 6	Special Needs	07/05/06	50.8	49.18	41.93	7.25
SMS	Farm 2 SMS 1	Lactating	07/05/06	93.2	6.84	2.53	4.31
SMS	Farm 2 SMS 2	Lactating	07/05/06	93.9	6.05	1.88	4.17
SMS	Farm 2 SMS 3	Lactating	07/05/06	92.7	7.27	3.08	4.19
SMS	Farm 2 SMS 4	Lactating	07/05/06	95.9	4.15	1.00	3.14
SMS	Farm 3 SMS 5	Special Needs	07/05/06	93.4	6.62	2.50	4.12
SMS	Farm 3 SMS 6	Special Needs	07/05/06	97.2	2.78	0.91	1.87
Manure	Farm 2 SMS 1	Lactating	07/28/06	82.3	17.70	1.72	15.97
Manure	Farm 2 SMS 2	Lactating	07/28/06	85.1	14.91	2.04	12.87
Manure	Farm 2 SMS 3	Lactating	07/28/06	86.1	13.92	1.50	12.42
Manure	Farm 2 SMS 4	Lactating	07/28/06	81.7	18.26	1.83	16.43
Manure	Farm 3 SMS 5	Special Needs	07/28/06	83.8	16.17	2.27	13.90
Manure	Farm 3 SMS 6	Special Needs	07/28/06	85.1	14.88	1.77	13.11
MINI	Farm 2 SMS 1	Lactating	07/28/06	95.8	4.24	1.20	3.04
MINI	Farm 2 SMS 2	Lactating	07/28/06	96.4	3.61	1.08	2.53
MINI	Farm 2 SMS 3	Lactating	07/28/06	95.0	5.05	1.51	3.53
MINI	Farm 2 SMS 4	Lactating	07/28/06	96.2	3.83	1.16	2.66
MINI	Farm 3 SMS 5	Special Needs	07/28/06	98.3	1.66	0.74	0.92
MINI	Farm 3 SMS 6	Special Needs	07/28/06	95.3	4.75	1.57	3.18
SLDM	Farm 2 SMS 1	Lactating	07/28/06	78.0	22.00	14.41	7.59
SLDM	Farm 2 SMS 2	Lactating	07/28/06	78.5	21.55	13.87	7.68
SLDM	Farm 2 SMS 3	Lactating	07/28/06	70.1	29.86	22.77	7.09
SLDM	Farm 2 SMS 4	Lactating	07/28/06	58.5	41.54	34.37	7.17
SLDM	Farm 3 SMS 5	Special Needs	07/28/06	76.0	23.97	16.49	7.48
SLDM	Farm 3 SMS 6	Special Needs	07/28/06	92.7	7.30	2.78	4.52
SMS	Farm 2 SMS 1	Lactating	07/28/06	95.7	4.33	1.25	3.08
SMS	Farm 2 SMS 2	Lactating	07/28/06	95.8	4.24		
SMS	Farm 2 SMS 3	Lactating	07/28/06	94.3	5.67	1.92	3.76
SMS	Farm 2 SMS 4	Lactating	07/28/06	94.4	5.63	1.37	4.26
SMS	Farm 3 SMS 5	Special Needs	07/28/06	97.9	2.10	0.84	1.25
SMS	Farm 3 SMS 6	Special Needs	07/28/06	94.7	5.34	1.74	3.60
Manure	Farm 2 SMS 1	Lactating	08/07/06	86.0	14.00	1.92	12.08
Manure	Farm 2 SMS 2	Lactating	08/07/06	84.4	15.62	2.27	13.34
Manure	Farm 2 SMS 3	Lactating	08/07/06	85.3	14.68	1.82	12.87
Manure	Farm 2 SMS 4	Lactating	08/07/06	84.4	15.62	2.36	13.27
Manure	Farm 3 SMS 5	Special Needs	08/07/06	84.7	15.33	2.66	12.67

Table B1: Solids concentration data from, GMF continued

Manure	Farm 3 SMS 6	Special Needs	08/07/06	85.6	14.42	2.53	11.89
MINI	Farm 2 SMS 1	Lactating	08/07/06	96.2	3.78	1.17	2.61
MINI	Farm 2 SMS 2	Lactating	08/07/06	97.0	2.98	0.97	2.01
MINI	Farm 2 SMS 3	Lactating	08/07/06	95.0	5.01	1.45	3.57
MINI	Farm 2 SMS 4	Lactating	08/07/06	95.3	4.69	1.38	3.32
MINI	Farm 3 SMS 5	Special Needs	08/07/06	95.1	4.88	1.61	3.27
MINI	Farm 3 SMS 6	Special Needs	08/07/06	94.2	5.82	1.74	4.08
SLDM	Farm 2 SMS 1	Lactating	08/07/06	85.2	14.85	6.79	8.06
SLDM	Farm 2 SMS 2	Lactating	08/07/06	86.0	14.00	6.29	7.71
SLDM	Farm 2 SMS 3	Lactating	08/07/06	76.1	23.93	15.75	8.18
SLDM	Farm 2 SMS 4	Lactating	08/07/06	68.8	31.17	23.50	7.67
SLDM	Farm 3 SMS 5	Special Needs	08/07/06	62.3	37.71	30.34	7.37
SLDM	Farm 3 SMS 6	Special Needs	08/07/06	87.4	12.57	7.91	4.66
SMS	Farm 2 SMS 1	Lactating	08/07/06	95.7	4.29	1.22	3.07
SMS	Farm 2 SMS 2	Lactating	08/07/06	97.2	2.83	0.95	1.88
SMS	Farm 2 SMS 3	Lactating	08/07/06	94.4	5.56	1.69	3.87
SMS	Farm 2 SMS 4	Lactating	08/07/06	95.1	4.90	1.50	3.40
SMS	Farm 3 SMS 5	Special Needs	08/07/06	95.1	4.85	1.70	3.15
SMS	Farm 3 SMS 6	Special Needs	08/07/06	95.3	4.71		
Manure	Farm 2 SMS 1	Lactating	08/21/06	85.0	15.02	2.27	12.74
Manure	Farm 2 SMS 2	Lactating	08/21/06	85.2	14.83	2.37	12.46
Manure	Farm 2 SMS 3	Lactating	08/21/06	85.9	14.11	1.98	12.13
Manure	Farm 2 SMS 4	Lactating	08/21/06	84.9	15.09	1.95	13.14
Manure	Farm 3 SMS 5	Special Needs	08/21/06	83.4	16.63	2.79	13.84
Manure	Farm 3 SMS 6	Special Needs	08/21/06	85.3	14.66	1.71	12.95
MINI	Farm 2 SMS 1	Lactating	08/21/06	94.4	5.61	1.56	4.05
MINI	Farm 2 SMS 2	Lactating	08/21/06	94.3	5.67	1.55	4.11
MINI	Farm 2 SMS 3	Lactating	08/21/06	95.7	4.28		
MINI	Farm 3 SMS 6	Special Needs	08/21/06	94.4	5.55	1.73	3.82
MINI			08/21/06	95.9	4.11	1.30	2.81
SLDM	Farm 2 SMS 1	Lactating	08/21/06	77.7	22.33	13.17	9.17
SLDM	Farm 2 SMS 2	Lactating	08/21/06	81.9	18.07	8.82	9.25
SLDM	Farm 2 SMS 3	Lactating	08/21/06	74.5	25.51	16.46	9.05
SLDM	Farm 3 SMS 6	Special Needs	08/21/06	90.4	9.65	4.47	5.18
SMS	Farm 2 SMS 1	Lactating	08/21/06	94.1	5.86	1.69	4.18
SMS	Farm 2 SMS 2	Lactating	08/21/06	93.4	6.55	2.06	4.50
SMS	Farm 2 SMS 3	Lactating	08/21/06	95.2	4.83	1.50	3.33
SMS	Farm 3 SMS 6	Special Needs	08/21/06	92.5	7.47	2.70	4.77
SMS			08/21/06	94.0	6.04	2.43	3.61
SLDM			09/26/06	65.6	34.35	26.84	7.51
SLDM			09/28/06	69.5	30.45	24.08	6.37

Table B1: Solids concentration data from, GMF continued

Manure	Farm 2 SMS 1	Lactating	03/23/07	85.6	14.43	1.93	12.50
Manure	Farm 2 SMS 2	Lactating	03/23/07	84.6	15.40	2.31	13.09
Manure	Farm 2 SMS 3	Lactating	03/23/07	84.2	15.77	2.63	13.13
Manure	Farm 2 SMS 4	Lactating	03/23/07	85.0	14.98	2.56	12.41
Manure	Farm 3 SMS 5	Special Needs	03/23/07	83.8	16.25	2.39	13.86
Manure	Farm 3 SMS 6	Special Needs	03/23/07	83.5	16.47	2.77	13.70
MINI	Farm 2 SMS 1	Lactating	03/23/07	93.6	6.41	2.17	4.23
MINI	Farm 2 SMS 2	Lactating	03/23/07	92.8	7.16	2.82	4.34
MINI	Farm 2 SMS 3	Lactating	03/23/07	93.6	6.41	1.70	4.71
MINI	Farm 2 SMS 4	Lactating	03/23/07	92.8	7.25	2.67	4.58
MINI	Farm 3 SMS 5	Special Needs	03/23/07	95.3	4.71	1.64	3.07
MINI	Farm 3 SMS 6	Special Needs	03/23/07	97.0	2.99	1.05	1.95
SLDM	Farm 2 SMS 1	Lactating	03/23/07	78.0	21.97	14.09	7.87
SLDM	Farm 2 SMS 2	Lactating	03/23/07	85.4	14.58	7.04	7.54
SLDM	Farm 2 SMS 3	Lactating	03/23/07	63.9	36.11	28.55	7.56
SLDM	Farm 2 SMS 4	Lactating	03/23/07	82.2	17.78	10.23	7.55
SLDM	Farm 3 SMS 5	Special Needs	03/23/07	64.8	35.20	28.12	7.09
SLDM	Farm 3 SMS 6	Special Needs	03/23/07	46.4	53.64	47.82	5.82
SMS	Farm 2 SMS 1	Lactating	03/23/07	90.4	9.61	4.97	4.64
SMS	Farm 2 SMS 2	Lactating	03/23/07	91.9	8.12	2.95	5.17
SMS	Farm 2 SMS 3	Lactating	03/23/07	88.9	11.12	6.36	4.76
SMS	Farm 2 SMS 4	Lactating	03/23/07	86.6	13.42	7.78	5.64
SMS	Farm 3 SMS 5	Special Needs	03/23/07	93.4	6.61	2.66	3.95
SMS	Farm 3 SMS 6	Special Needs	03/23/07	93.2	6.85	3.25	3.60
MINI	Farm 2 SMS 4	Lactating	06/26/07	95.0	5.03	1.69	3.33
SLDM	Farm 2 SMS 2	Lactating	06/26/07	64.9	35.15	27.36	7.79
SMS	Farm 2 SMS 3	Lactating	06/26/07	93.1	6.91	3.14	3.78
MINI			07/10/07	94.5	5.53	1.73	3.80
SLDM			07/10/07	62.3	37.75	30.25	7.50
SMS			07/10/07	92.9	7.10	3.20	3.90
MINI	Farm 2 SMS 3	Lactating	07/20/07	94.1	5.85	1.84	4.01
SLDM	Farm 2 SMS 1	Lactating	07/20/07	65.9	34.07	25.11	8.96
SMS	Farm 2 SMS 2	Lactating	07/20/07	91.3	8.73	4.26	4.46

Table B2: Total solids concentration data, GMF

Sample Location	Mean TS (%)	Standard Deviation (%)	Coefficient of Variation (%)	Median (%)	Number of Samples
Feces	14.9	2.0	13.7	14.9	70
SLDM	28.3	11.0	36.4	30.3	69
SMS	6.0	2.0	33.5	6.0	56
MINI	4.9	1.3	26.0	5.0	71
HC Overflow	4.1	1.2	27.6	4.4	40

Table B3: Fixed solids concentration data, GMF

Sample Location	Mean FS (%)	Standard Deviation (%)	Coefficient of Variation (%)	Median (%)	Number of Samples
Feces	2.2	1.2	60.1	1.9	68
SLDM	20.7	10.4	47.8	21.9	69
SMS	2.3	1.3	63.0	2.1	54
MINI	1.5	0.4	28.8	1.4	70
HC Overflow	1.1	0.5	42.6	1.2	40

Table B4: Volatile solids concentration data, GMF

Sample Location	Mean VS (%)	Standard Deviation (%)	Coefficient of Variation (%)	Median (%)	Number of Samples
Feces	12.6	1.7	13.3	12.5	68
SLDM	7.6	1.4	17.6	8.0	69
SMS	3.7	0.9	24.4	3.8	54
MINI	3.4	1.0	27.0	3.5	70
HC Overflow	3.0	1.1	34.1	3.2	40

Table B5: Individual FS, Type III tests of fixed effects (ANOVA), GMF

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr > F
trt	3	31.43	23.39	<0.0001
mgt	1	49.55	0.11	0.7464
trt*mgt	3	31.43	0.35	0.7912

Table B6: Individual FS, trt least squares means, GMF

Level	Estimate	Standard Error	Degrees of Freedom	t value	Pr > |t|
Manure	8.2886	0.3658	104.8	22.66	<0.0001
SLDM	8.7643	0.27	39.63	32.47	<0.0001
SMS	10.6894	0.1817	7.841	58.83	<0.0001
MINI	9.2301	0.2326	22.4	39.68	<0.0001

Table B7: Individual FS, trt least squares means confidence interval, GMF

Treatment Level	Mean	Standard Error	95% Confidence Interval Lower	Upper	Count
	(kg/d)	(kg/d)	(kg/d)	(kg/d)	
Manure	3,978	1,455	1,926	8,217	68
SLDM	43,887	7,975	28,821	66,828	64
SMS	10,199	2,373	6,299	16,515	50
MINI	6,402	1,728	3,709	11,049	67

Table B8: Individual FS, Differences of trt least squares means, GMF

Treatment Level	Estimate	Standard Error	Degrees of Freedom	t value	Pr > |t|
Manure vs. SLDM	-2.4008	0.3923	62.08	-6.12	<0.0001
SLDM vs. SMS	1.4593	0.2728	16.57	5.35	<0.0001
SMS vs. MINI	-0.4657	0.3383	37.59	-1.38	0.1768

Table B9: Individual VS, Type III tests of fixed effect (ANOVA), GMF

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr > F
trt	2	1	8.09	0.2413
mgt	1	1	9.52	0.1995
trt*mgt	2	1	0.51	0.7022

Table B10: Individual VS, trt least squares means

Treatment Level	Estimate	Standard Error	Degrees of Freedom	t value	Pr > |t|
SLDM	21,259	1,326	1	16.03	0.0397
SMS	18,738	1,347	1	13.91	0.0457
MINI	15,846	1,321	1	12	0.0529

Table B11: Individual VS, trt least squares means confidence interval, GMF

Treatment Level	Mean (kg/d)	Standard Error (kg/d)	95% Confidence Interval Lower (kg/d)	95% Confidence Interval Upper (kg/d)	Count
SLDM	21,259	1,326	4,410	38,109	64
SMS	18,738	1,347	1,626	35,851	50
MINI	15,846	1,321	-937	32,629	67

Table B12: Individual VS, Differences of trt least squares means, GMF

Treatment Level	Estimate	Standard Error	Degrees of Freedom	t value	Pr > |t|
SLDM vs. SMS	2,520	1,379	1	1.83	0.3187
SMS vs. MINI	-2,892	1,373	1	-2.11	0.2821

Table B13: HC FS, Type III tests of fixed effects (ANOVA), GMF

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr > F
trt	1	20	13.21	0.0017

Table B14: HC FS, trt least squares means

Treatment Level	Estimate	Standard Error	Degrees of Freedom	t value	Pr > |t|
MINI	6,395	269	20	23.79	<0.0001
HC overflow	5,014	269	20	18.65	<0.0001

Table B15: HC FS, trt least squares means confidence interval, GMF

Treatment Level	Mean (kg/d)	Standard Error (kg/d)	95% Confidence Interval Lower (kg/d)	95% Confidence Interval Upper (kg/d)	Count
MINI	6,395	269	5,835	6,956	12
HC overflow	5,014	269	4,453	5,574	12

Table B16: HC FS, Differences of trt least squares means, GMF

Treatment Level	Estimate	Standard Error	Degrees of Freedom	t value	Pr > |t|
HC vs. MINI	-1,381	380	20	-3.63	0.0017

Table B17: HC VS, Type III tests of fixed effects (ANOVA), GMF

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr > F
trt	1	20	1.36	0.2568

Table B18: HC VS, trt least squares means

Treatment Level	Estimate	Standard Error	Degrees of Freedom	t value	Pr > |t|
MINI	15,154	895	20	16.94	<0.0001
HC overflow	13,677	895	20	15.29	<0.0001

Table B19: HC VS, trt least squares means confidence interval, GMF

Treatment Level	Mean	Standard Error	95% Confidence Interval		Count
			Lower	Upper	
	(kg/d)	(kg/d)	(kg/d)	(kg/d)	
MINI	15,154	895	13,288	17,020	11
HC overflow	13,677	895	11,811	15,543	11

Table B20: HC VS, Differences of trt least squares means, GMF

Treatment Level	Estimate	Standard Error	Degrees of Freedom	t value	Pr > |t|
HC vs. MINI	-1,477	1,265	20	-1.17	0.2568

APPENDIX C

MDF Sand Separation Mass Balance Data

Table C1: SSS flow rate (L/s), MDF

Sample Point	Description	Sample Event 1 (L/s)	Sample Event 2 (L/s)	Sample Event 3 (L/s)	Mean (L/s)	Standard Deviation (L/s)	Coefficient of Variation
1	Fresh water	0.16	0.20	0.19	0.18	0.02	10%
2	Recycled water	3.71	3.71	4.46	3.96	0.43	11%
3	SLDM	0.91	0.92	0.97	0.93	0.03	4%
4	SSS reclaimed sand	0.05	0.06	0.11	0.07	0.03	42%
5	SMS liquid effluent	4.26	3.91	5.30	4.49	0.72	16%
5a	HC input	8.77	8.58	9.56	8.97	0.52	6%
6	HC overflow	7.91	7.73	8.02	7.89	0.15	2%
7	HC underflow	0.12	0.41	0.17	0.24	0.15	65%
	SMS dilution ratio:	4.1	4.0	4.6	4.2	0.3	

Table C2: SSS flow rate (m^3/hr), MDF

Sample Point	Description	Sample Event 1 (m^3/hr)	Sample Event 2 (m^3/hr)	Sample Event 3 (m^3/hr)	Mean (m^3/hr)	Standard Deviation (m^3/hr)	Coefficient of Variation
1	Fresh water	0.58	0.71	0.69	0.7	0.1	10%
2	Recycled water	13.37	13.36	16.07	14.3	1.6	11%
3	SLDM	2.75	2.89	3.12	2.9	0.2	6%
4	SSS reclaimed sand	0.18	0.22	0.39	0.3	0.1	42%
5	SMS liquid effluent	15.33	14.08	19.07	16.2	2.6	16%
5a	HC input	24.23	23.72	26.43	24.8	1.4	6%
6	HC overflow	21.86	21.36	22.16	21.8	0.4	2%
7	HC underflow	0.34	1.14	0.48	0.7	0.4	65%
	SMS percent closure:	9%	21%	4%	11%	9%	
	HC percent closure:	8%	5%	14%	9%	5%	
	SSS percent closure:	-32%	-27%	-13%	-24%	10%	
	SMS dilution ratio:	4.9	4.6	5.2	4.9	0.3	

[1]SLDM flow rate based was based on the daily measured piston pump cycle time (down and up-stroke) minus the up-stroke.

[2]Cyclone flow rate was based on a measured runtime of 46 minute per hour.

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Table C3: Material density, MDF

Sample Point	Description	Sample Event 1 (kg/m³)	Sample Event 2 (kg/m³)	Sample Event 3 (kg/m³)	Mean (kg/m³)	Standard Deviation (kg/m³)	Coefficient of Variation
1	Fresh water	997	1,005	1,000	1,000	4	0%
2	Recycled water	1,015		1,037	1,026		
3	SLDM[1]	1,092		1,003	1,048		
4	SSS reclaimed sand	2,038	1,708	1,617	1,787	221	12%
5	SMS liquid effluent	1,024	1,059	1,035	1,039	18	2%
5a	HC input[2]	1,024	1,059	1,035	1,039	18	2%
6	HC overflow	1,026	1,004	1,024	1,018	12	1%
7	HC underflow	1,653	1,149	1,371	1,391	253	18%

Table C4: SSS mass flow rate, MDF

Sample Point	Description	Sample Event 1 (kg/hr)	Sample Event 2 (kg/hr)	Sample Event 3 (kg/hr)	Mean (kg/hr)	Standard Deviation (kg/hr)	Coefficient of Variation
1	Fresh water	580	710	691	660	70	11%
2	Recycled water	13,573	10,987	16,669	13,743	2,845	21%
3	SLDM[1]	3,007	2,694	3,127	2,943	223	8%
4	SSS reclaimed sand	361	384	629	458	148	32%
5	SMS liquid effluent	15,695	14,913	19,730	16,779	2,585	15%
5a	HC input[2]	24,813	25,125	27,344	25,761	1,380	5%
6	HC overflow	22,443	21,449	22,689	22,194	656	3%
7	HC underflow	564	1,306	654	841	405	48%
	SMS percent closure:	9%	3%	4%	5%	4%	
	HC percent closure:	7%	9%	15%	10%	4%	
	SSS percent closure:	-33%	-52%	-14%	-33%	19%	

[1]SLDM flow rate based was based on the daily measured piston pump cycle time (down and up-stroke) minus the up-stroke.

[2]Cyclone flow rate was based on a measured runtime of 46 minute per hour.

Table C5: TS concentration, MDF

Sample Point	Description	Sample Event 1 (%)	Sample Event 2 (%)	Sample Event 3 (%)	Mean (%)	Standard Deviation (%)
1	Fresh water	0.1	0.2	0.1	0.1	0.1
2	Recycled water	4.2	4.2	4.5	4.3	0.2
3	SLDM[1]	14.1	20.0	10.7	14.9	4.7
4	SSS reclaimed sand	59.1	72.5	77.2	69.6	9.4
5	SMS liquid effluent	3.9	5.7	5.6	5.0	1.0
5a	HC input[2]	3.9	5.7	5.6	5.0	1.0
6	HC overflow	3.9	5.0	4.3	4.4	0.6

Table C6: SSS TS mass flow rate, MDF

Sample Point	Description	Sample Event 1 (kg/hr)	Sample Event 2 (kg/hr)	Sample Event 3 (kg/hr)	Mean (kg/hr)	Standard Deviation (kg/hr)	Coefficient of Variation
1	Fresh water	0.5	1.2	0.4	0.7	0.4	59%
2	Recycled water	565	467	745	592	141	24%
3	SLDM[1]	425	539	333	432	103	24%
4	SSS reclaimed sand	213	279	485	326	142	44%
5	SMS liquid effluent	610	844	1095	850	243	29%
5a	HC input[2]	964	1422	1518	1,301	296	23%
6	HC overflow	876	1073	974	975	98	10%
7	HC underflow	241	468		355		
	SMS percent closure:	133%	124%	53%	104%	44%	
	HC percent closure:	86%	92%		89%		
	SSS percent closure:	90%	66%	65%	73%	14%	

[1]SLDM flow rate based on the measured piston pump downstroke, upstroke deducted

[2]Cyclone flow rate based on measured runtime of 46 minute per hour

Table C7: FS concentration, MDF

Sample Point	Description	Sample Event 1 (%)	Sample Event 2 (%)	Sample Event 3 (%)	Mean (%)	Standard Deviation (%)
1	Fresh water	0.0	0.2	0.0	0.1	0.1
2	Recycled water	1.4	1.7	1.8	1.6	0.2
3	SLDM[1]	8.3	13.9	7.5	9.9	3.5
4	SSS reclaimed sand	57.9	69.9	74.7	67.5	8.6
5	SMS liquid effluent	1.5	2.8	2.3	2.2	0.6
5a	HC input[2]	1.5	2.8	2.3	2.2	0.6
6	HC overflow	1.1	1.8	1.4	1.4	0.4
7	HC underflow	40.6	34.1		37.4	4.6

Table C8: SSS FS mass flow rate, MDF

Sample Point	Description	Sample Event 1 (kg/hr)	Sample Event 2 (kg/hr)	Sample Event 3 (kg/hr)	Mean (kg/hr)	Standard Deviation (lb/hr)	Coefficient of Variation
1	Fresh water	-0.2	1.1	0.2	0.4	0.7	174%
2	Recycled water	188.5	183.2	292.6	221	62	28%
3	SLDM[1]	250.0	375.1	234.7	287	77	27%
4	SSS reclaimed sand	209.3	268.3	469.9	316	137	43%
5	SMS liquid effluent	238.6	411.6	452.2	367	113	31%
5a	HC input[2]	377.2	693.5	626.7	566	167	29%
6	HC overflow	240.3	381.8	324.2	315	71	23%
7	HC underflow	229.1	445.1		337		
	SMS percent closure:	33%	32%	-75%	-3%	62%	
	HC percent closure:	-24%	-19%		-22%		
	SSS percent closure:	-3%	-16%	-51%	-23%	25%	

[1]SLDM flow rate based on the measured piston pump downstroke, upstroke deducted

[2]Cyclone flow rate based on measured runtime of 46 minute per hour

Table C9: VS concentration, MDF

Sample Point	Description	Sample Event 1 (%)	Sample Event 2 (%)	Sample Event 3 (%)	Mean (%)	Standard Deviation (%)
1	Fresh water	0.1	0.0	0.0	0.1	0.1
2	Recycled water	2.8	2.6	2.7	2.7	0.1
3	SLDM	5.8	6.1	3.2	5.0	1.6
4	SSS reclaimed sand	1.1	2.6	2.4	2.1	0.8
5	SMS liquid effluent	2.4	2.9	3.3	2.8	0.4
5a	HC input	2.4	2.9	3.3	2.8	0.4
6	HC overflow	2.8	3.2	2.9	3.0	0.2
7	HC underflow	2.2	1.8		2.0	0.3

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Table C10: SSS VS mass flow rate, MDF

Sample Point	Description	Sample Event 1 (kg/hr)	Sample Event 2 (kg/hr)	Sample Event 3 (kg/hr)	Mean (kg/hr)	Standard Deviation (lb/hr)	Coefficient of Variation
1	Fresh water	0.7	0.1	0.2	0.3	0.3	97%
2	Recycled water	376.6	283.3	452.0	371	84	23%
3	SLDM[1]	175.1	163.6	98.8	146	41	28%
4	SSS reclaimed sand	4.0	10.2	15.4	10	6	58%
5	SMS liquid effluent	371.3	432.3	642.9	482	142	30%
5a	HC input[2]	587.0	728.3	891.0	735	152	21%
6	HC overflow	636.2	691.2	650.1	659	29	4%
7	HC underflow	12.3	22.9		18		
	SMS percent closure:	34%	6%	-19%	7%	27%	
	HC percent closure:	-10%	2%		-4%		
	SSS percent closure:	-16%	-57%	-21%	-31%	22%	

[1]SLDM flow rate based on the measured piston pump downstroke, upstroke deducted

[2]Cyclone flow rate based on measured runtime of 46 minute per hour

Table C11: SSS TS separation efficiency, MDF

Component	Sample Event 1	Sample Event 2	Sample Event 3	Mean	Standard Deviation
SMS:	17%	19%	45%	27%	16%
HC:	25%	33%		29%	
SSS:	22%	28%	45%	31%	12%

Table C12: SSS FS separation efficiency, MDF

Component	Sample Event 1	Sample Event 2	Sample Event 3	Mean	Standard Deviation
SMS:	31%	27%	89%	49%	35%
HC:	61%	64%		62%	
SSS:	48%	48%	89%	62%	24%

Table C13: Piston pump speed measurements

Component	Sample Event 1	Sample Event 2	Sample Event 3	Mean	Standard Deviation	Coefficient of Variation
Down-stroke, s:	157.6	170.8	211.5	180.0	28.1	16%
Up-stroke, s:	29.4	25.8	23.7	26.3	2.9	11%
Cycle time, s:	187	196.6	235.2	206	25.5	12%
Pump cycles per hr:	19.3	18.3	15.3	17.6	2.1	12%
On-time, min/hr:	50.6	52.1	54.0	52.2	1.7	3%

Table C14: SMS effluent rate, 45 minutes sample period

Sample #[1]	Time (min)	Weight (kg)	Volume (m^3)	Density (kg/m^3)	Flow Rate (m^3/min)	Mass Flow (kg/min)	FS (%)	FS Flow (kg/min)
1	2	10	0.01	919.10	0.5	480	0.62	2.99
2	4	13.409	0.01	924.32	0.4	374	1.62	3.92
3	6	14.773	0.02	928.09	0.5	457	2.62	4.86
4	8	12.955	0.01	931.81	0.5	508	3.62	3.74
5	10	12.727	0.01	915.46	0.5	468	4.62	4.35
6	12	15.682	0.02	937.72	0.4	390	5.62	3.98
7	14	16.591	0.02	935.71	0.6	524	6.62	8.11
8	**16**	16.818	0.02	937.87	0.5	476	7.62	5.85
9	18	15.455	0.02	935.40	0.5	444	8.62	9.37
10	20	16.591	0.02	914.92	0.3	312	9.62	7.20
11	22	13.864	0.02	905.35	0.6	520	10.62	7.01
12	24	12.5	0.01	939.98	0.6	521	11.62	11.80
13	26	17.727	0.02	935.98	0.5	467	12.62	7.27
14	**28**	17.045	0.02	939.98	0.5	424	13.62	6.78
15	**30**	15.455	0.02	913.13	0.5	444	14.62	9.73
16	32	15.227	0.02	933.02	0.5	431	15.62	9.27
17	*34*	17.955	0.02	938.01	0.5	472	16.62	7.78
18	*35.5*	15.227	0.02	921.64	0.6	513	17.62	7.45
19	*37*	15.227	0.02	933.02	0.4	412	18.62	7.91
20	38.5	13.182	0.01	934.61	0.4	390	19.62	7.59
21	**40**	15.682	0.02	937.72	0.5	485	20.62	7.82
22	41.5	12.5	0.01	912.34	0.4	408	21.62	5.99
23	43	15	0.02	942.36	0.4	393	22.62	6.00
24	44.5	13.636	0.01	914.58	0.4	401	23.62	8.15

[1]**Bold piston pump off,** *italic hydrocyclone off*

APPENDIX D

GMF Particle Size Data

Table D1: New sand PSD

Sieve Opening (mm)	Percent Passing Sample Event							Mean	Standard Deviation
	01/05/07	06/18/07	06/26/07	07/20/07	10/29/07	11/09/07	11/30/07		
4.75	100	100	99	99	99	100	100	100	1
2.36	87	88	87	85	85	91	90	88	2
1.18	66	69	69	68	64	78	70	69	4
0.60	41	45	49	48	43	53	39	45	5
0.30	7	12	17	16	16	8	7	12	5
0.149	1	2	2	3	3	1	1	2	1
0.074	0	1	0	1	0	1	0	0	1
Pan	0	0	0	0	0	0	0	0	0

Table D2: Reclaimed sand PSD

Sieve Opening (mm)	Percent Passing Sample Event							Mean	Standard Deviation
	01/05/07	06/18/07	06/26/07	07/20/07	10/29/07	11/09/07	11/30/07		
4.75	100	100	100	99	99	98	100	99	1
2.36	87	85	83	85	72	80	90	83	6
1.18	64	63	60	65	43	55	73	60	9
0.60	36	35	32	39	16	28	44	33	9
0.30	3	4	4	6	1	4	3	4	2
0.149	0	0	1	0	0	0	0	0	0
0.074	0	0	0	0	0	0	0	0	0
Pan	0	0	1	0	0	0	0	0	0

Table D3: HC underflow PSD

Sieve Opening (mm)	Percent Passing Sample Event					Mean	Standard Deviation
	06/18/07	06/26/07	07/20/07	10/29/07	11/09/07		
4.75	99	100	100	86	79	93	10
2.36	94	96	97	79	71	87	12
1.18	80	85	88	68	64	77	11
0.60	61	62	75	52	57	61	9
0.30	35	36	47	32	34	37	6
0.149	13	13	1	9	4	8	5
0.074	5	3	0	1	1	2	2
Pan	4	1	0	0	0	1	2

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Table D4: HC overflow PSD

Sieve Opening (mm)	Percent Passing / Sample Event					Mean	Standard Deviation
	01/05/07	01/28/08	01/28/08	04/11/08	04/11/08		
4.75	100	93	97	99	98	97	3
2.36	99	90	96	98	96	96	3
1.18	98	88	94	96	94	94	4
0.60	91	84	90	92	89	89	3
0.30	51	68	72	85	83	72	14
0.149	13	28	28	61	65	39	23
0.074	0	7	7	16	21	10	8
Pan	-1	0	0	-5	-1	-1	2

Table D5: Tank sludge PSD

Sieve Opening (mm)	Percent Passing							
	Sample Event*						Mean	Standard Deviation
	05/23/07			10/02/08				
	1	2	Mean	1	2	Mean		
4.75	98	99	99	92	94	93	96	3
2.36	92	96	94	89	91	90	92	3
1.18	83	90	87	85	88	87	87	3
0.60	68	81	75	78	83	81	78	7
0.30	47	62	55	69	75	72	63	12
0.149	20	29	25	45	53	49	37	15
0.074	3	5	4	11	15	13	9	6
Pan	0	0	0	-2	0	-1	-1	1

* 5/23/07 post digester equalization tanke sludge, 10/2/2008 AD tank 3 sludge

APPENDIX E

GMF Solids Data from Other Sample Locations

Table E1: Anaerobic Digester Effluent

Sample ID	Sample Date	Moisture (%)	TS (%)	FS (%)	VS (%)
Digester effluent	10/25/2007	98.83	1.17	1.16	0.01
Digester effluent	10/25/2007	93.48	6.52	1.11	5.41
Digester effluent	10/29/2007	97.29	2.71	1.20	1.51
Digester effluent	11/11/2007	97.49	2.51	1.08	1.43
Digester effluent	11/13/2007	97.37	2.63	1.17	1.46
Digester effluent	11/30/2007	97.11	2.89	1.00	1.89
Digester effluent	11/30/2007	97.54	2.46	0.84	1.62
Digester effluent	12/3/2007	97.33	2.67	1.02	1.64
Digester effluent	12/5/2007	98.66	1.34	0.64	0.70
Digester effluent	12/9/2007	98.07	1.93	0.87	1.07

	Moisture (%)	TS (%)	FS (%)	VS (%)
Average	97.3	2.7	1.0	1.7
Standard deviation	1.5	1.5	0.2	1.4
Median	97.4	2.6	1.1	1.5
Count	10	10	10	10

Table E2: HC Underflow

Sample ID	Sample Date	Moisture (%)	TS (%)	FS (%)	VS (%)
HC underflow	3/23/2007	77.29	22.71	15.45	7.25
HC underflow	6/26/2007	89.60	10.40	4.38	6.02
HC underflow	7/9/2007	96.64	3.36	0.92	2.44
HC underflow	7/10/2007	93.07	6.93	2.55	4.38
HC underflow	7/20/2007	81.10	18.90	11.74	7.16
HC underflow	12/9/2007	98.14	1.86	0.57	1.29
HC underflow	12/9/2007	98.45	1.55	0.45	1.09

	Moisture (%)	TS (%)	FS (%)	VS (%)
Average	90.6	9.4	5.2	4.2
Standard deviation	8.5	8.5	6.0	2.7
Median	93.1	6.9	2.6	4.4
Count	7	7	7	7

Table E3: Post AD Equalization Tank Sludge

Sample ID	Sample Date	Moisture (%)	TS (%)	FS (%)	VS (%)
Tank Sludge I	5/23/2007	53.05	46.95	36.61	10.35
Tank Sludge I	5/23/2007	59.15	40.85	29.72	11.13
Tank Sludge II	5/23/2007	44.69	55.31	47.16	8.15
Tank Sludge II	5/23/2007	51.08	48.92	38.99	9.94

	Moisture (%)	TS (%)	FS (%)	VS (%)
Average	52.0	48.0	38.1	9.9
Standard deviation	6.0	6.0	7.2	1.3
Median	52.1	47.9	37.8	10.1
Count	4	4	4	4

Table E4: New Sand

Sample ID	Sample Date	Moisture (%)	TS (%)	FS (%)	VS (%)
New Sand	6/26/2007	3.61	96.39	94.66	1.73
New Sand	7/9/2007	2.43	97.57	95.37	2.19
New Sand	7/20/2007	3.90	96.10	94.29	1.82
New Sand	12/9/2007	4.20	95.80	92.81	2.99

	Moisture (%)	TS (%)	FS (%)	VS (%)
Average	3.5	96.5	94.3	2.2
Standard deviation	0.8	0.8	1.1	0.6
Median	3.8	96.2	94.5	2.0
Count	4	4	4	4

Table E5: Reclaimed Sand

Sample ID	Sample Location	Herd Management	Sample Date	Moisture (%)	TS (%)	FS (%)	VS (%)
Reclaimed sand	Farm 2 SMS 1	Lactating	7/5/2006	16.08	83.92	82.42	1.50
Reclaimed sand	Farm 2 SMS 2	Lactating	7/5/2006	15.99	84.01	81.80	2.21
Reclaimed sand	Farm 2 SMS 3	Lactating	7/5/2006				
Reclaimed sand	Farm 2 SMS 4	Lactating	7/5/2006	24.16	75.84	72.70	3.14
Reclaimed sand	Farm 2 SMS 1	Lactating	7/28/2006	8.68	91.32	89.08	2.24
Reclaimed sand	Farm 2 SMS 2	Lactating	7/28/2006	12.29	87.71	83.78	3.93
Reclaimed sand	Farm 2 SMS 3	Lactating	7/28/2006	12.38	87.62	83.90	3.72
Reclaimed sand	Farm 2 SMS 4	Lactating	7/28/2006	13.43	86.57	82.00	4.57
Reclaimed sand	Farm 2 SMS 1	Lactating	8/7/2006	15.95	84.05	79.81	4.24
Reclaimed sand	Farm 2 SMS 2	Lactating	8/7/2006	26.78	73.22	65.96	7.26
Reclaimed sand	Farm 2 SMS 3	Lactating	8/7/2006	20.41	79.59	76.22	3.37
Reclaimed sand	Farm 2 SMS 4	Lactating	8/7/2006	12.64	87.36	84.14	3.22
Reclaimed sand	Farm 2 SMS 1	Lactating	8/21/2006	10.67	89.33	86.68	2.65
Reclaimed sand	Farm 2 SMS 2	Lactating	8/21/2006	12.72	87.28	83.93	3.35
Reclaimed sand	Farm 2 SMS 3	Lactating	8/21/2006	16.37	83.63	78.54	5.09
Reclaimed sand	Farm 2 SMS 4	Lactating	8/21/2006	7.34	92.66	90.33	2.33
Reclaimed sand	Farm 2 SMS 1	Lactating	3/23/2007	20.58	79.42	76.61	2.82
Reclaimed sand	Farm 2 SMS 2	Lactating	3/23/2007	13.45	86.55	84.75	1.80
Reclaimed sand	Farm 2 SMS 3	Lactating	3/23/2007	19.34	80.66	77.57	3.09
Reclaimed sand	Farm 2 SMS 4	Lactating	3/23/2007	10.79	89.21	87.18	2.02
Reclaimed sand	Farm 2 SMS 1	Lactating	7/20/2007	12.05	87.95	84.87	3.08
Reclaimed sand	Farm 3 SMS 5	Special Needs	7/5/2006	23.62	76.38	71.74	4.64
Reclaimed sand	Farm 3 SMS 6	Special Needs	7/5/2006	26.07	73.93	69.32	4.61
Reclaimed sand	Farm 3 SMS 5	Special Needs	7/28/2006	12.20	87.80	84.44	3.36
Reclaimed sand	Farm 3 SMS 6	Special Needs	7/28/2006	17.79	82.21	79.33	2.89
Reclaimed sand	Farm 3 SMS 5	Special Needs	8/7/2006	11.01	88.99	86.19	2.80
Reclaimed sand	Farm 3 SMS 6	Special Needs	8/7/2006				
Reclaimed sand	Farm 3 SMS 5	Special Needs	8/21/2006	11.62	88.38	85.57	2.81
Reclaimed sand	Farm 3 SMS 6	Special Needs	8/21/2006	23.35	76.65	71.70	4.95
Reclaimed sand	Farm 3 SMS 5	Special Needs	3/23/2007	13.91	86.09	84.40	1.69
Reclaimed sand	Farm 3 SMS 6	Special Needs	3/23/2007	24.23	75.77	72.93	2.83
Reclaimed sand			6/26/2007	13.41	86.59	84.20	2.39
Reclaimed sand			7/9/2007	8.89	91.11	86.91	4.20
Reclaimed sand			12/9/2007	26.10	73.90	70.08	3.82

	Moisture (%)	TS (%)	FS (%)	VS (%)
Average	16.1	83.9	80.6	3.3
Standard deviation	5.7	5.7	6.4	1.2
Median	13.7	86.3	83.1	3.1
Count	32	32	32	32

APPENDIX F

Anaerobic Digester Systems – Operation Data

Table F1: Operational Data from Several U.S. Based Anaerobic Digesters

Anaerobic Digester Type	Total Number of Systems	Mean Number of Animals	Installed Generation Capacity			
			Number of Systems	Mean		Standard Deviation
				(kW)	(animals/kW)	(animals/kW)
Complete Mix	26	1,628	22	415	4.7	2.6
Covered Lagoon	10	1,778	8	247	9.2	6.3
Fixed Film	1	250	1	30	8.3	
Horizontal Plug Flow	32	1,621	30	330	7.2	3.8
Induced Blanket Reactor	2	775	2	100	7.5	
Mixed Plug Flow	33	2,878	27	589	4.2	1.1

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