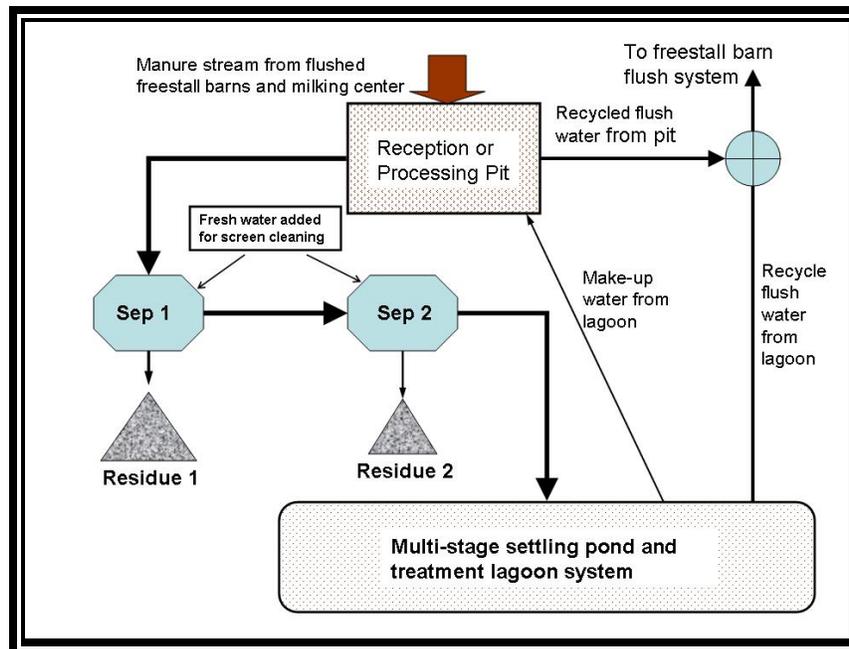


Field Evaluation of a Two-Stage Liquid-Solid Separation System at a California Dairy



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Introduction

California is the largest milk producing state in the United States producing 21.6% of the nations milk supply. In August 2008 the milking herd in California numbered 1,843,000 head, with an annual milk production of 3,400 million pounds (NASS, 2008).

Over the last several years, many California dairy producers have converted their animal housing from open lots to flushed freestall barns and flushed milking centers to gain efficiency and to improve their ability to manage the large amount of manure produced by the animals (17.5 gal/cow-/day).

An integral part of this conversion of their animal housing facilities from open lots to freestall barns has been the addition of mechanical liquid-solid separation to provide primary treatment of flushed dairy manure. One of the most popular types of mechanical separator is the inclined static screen. However, many of the first inclined screen separators used large screen sizes ranging from 0.059 to 0.066 inches (1.5 to 1.68 mm) based on data collected from dairies located in the Eastern and Midwestern regions of the US (e.g. Chastain et al., 2001; Fulhage and Hoehne, 1998; and Zhang and Westerman, 1997). Results from these studies indicated that 46% to 61% of the total solids in flushed dairy manure could be removed using an inclined screen. However, field experience in California indicated that such screen sizes could only remove on the order of 10% to 20% of the TS. The reason for the discrepancy was the vast differences in the amount and type of bedding used, and the lower TS content of flushed manure on California dairy farms.

In response to these field experiences US Farm Systems has developed improved mechanical separators that use screen sizes ranging from 0.010 to 0.035 inches (0.254 to 0.889 mm) and multi-stage systems to provide higher solids removal on California dairy farms. The separated solids are also recycled back into the operation as freestall bedding.

A new, two-stage mechanical separation system was developed by US Farm Systems and was installed on the Bos Dairy Farm in Tulare, California. The system included two inclined separators operated in series. The first separator had a 0.020 in screen and the second used a 0.010 inch screen. Dried residue (separated solids) from the first screen was used for freestall bedding. The effluent from the second separator received additional treatment in a series of settling ponds and a treatment lagoon.

The objectives of this study were to: (1) evaluate the performance of the two-stage liquid-solid separation system, (2) determine the composition of the system effluent, (3) evaluate key settling characteristics of the effluent from the separation system (4) determine the composition of the separated solids from both stages, and (5) determine the composition of the dried separated solids used for freestall bedding.

Methods

The Bos Dairy farm, located in Tulare CA, began milking about 1750 cows in 1982. In 2001 a new freestall complex and milking center was begun. The waste treatment and storage system included a reception, or processing pit, an inclined screen separator, settling ponds, and a treatment lagoon. Supernatant from the final treatment lagoon was the primary source of flush water for the freestall barns. By 2002 the dairy had expanded to 3450 cows and by late 2006 the herd had increased to 3600 cows producing an average of 69.9 lb of milk per cow per day.

Several modifications were made to the manure treatment system as the dairy was expanded. Today the manure treatment system consists of a processing pit that is used to collect flushed manure from the freestall barns and milking center, two inclined screen separators operating in series, and a series of four settling ponds and a final treatment lagoon (Figure 1).

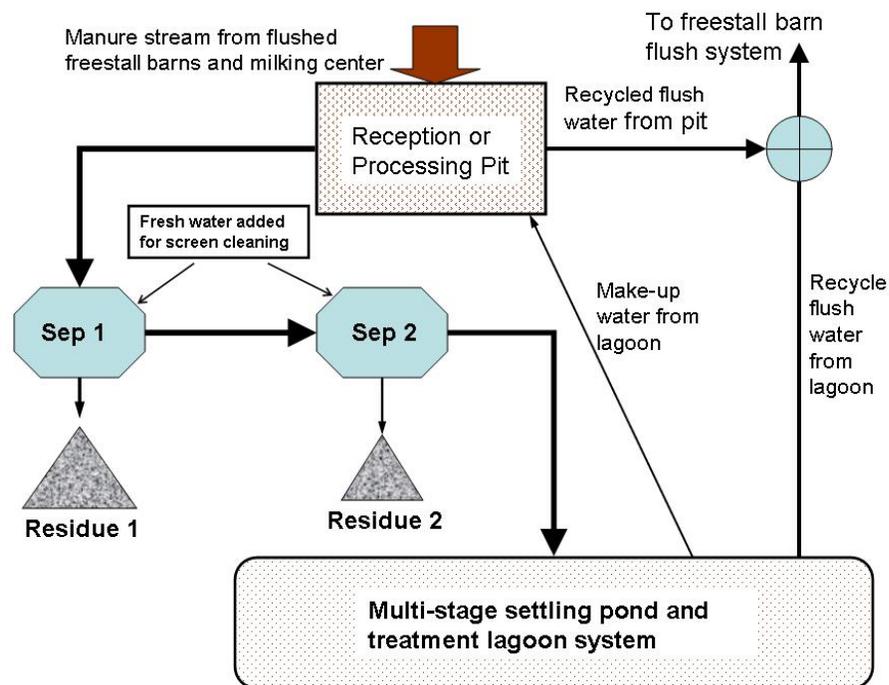


Figure 1. Flow diagram for the manure treatment system at the Bos Dairy.

Manure from the dairy facilities is flushed eight times a day and is collected in a processing pit. Initially, water from the final lagoon was used to flush freestall alleys. At the present, supernatant from the processing pit is used for alley flushing. Water is resupplied to the processing pit as needed from the final lagoon.

When the liquid level exceeds the set point the pit contents are agitated and pumped to the first separator. The first incline screen separator has a bar screen with a mean opening size of 0.020 in (0.508 mm). The separated solids slide down the screen and are collected in a trough where a low-pressure screw press provides additional dewatering and conveys the solids to an inclined screen stacking conveyor. The separated solids, or residue, are stored temporarily on a concrete pad. Periodically the solids from the first separator are spread in layers in a lot between the

freestall barns. The solids are disked periodically to enhance drying and exposure to solar radiation. Once the solids are dry they are stored in large covered windrows. The dried separated solids are recycled through the dairy facility as freestall bedding.

The effluent from the first separator is pumped to a second inclined screen separator with a screen size of 0.010 in (0.254 mm). The wet solids are collected on another inclined screen stacking conveyor and are stored on a stacking pad. The conveyor provides additional drying of the solids so that they will be of stackable moisture content. The separated solids from the second separator are land applied on near-by cropland.

Both of the inclined screen separators utilize fresh water sprays to keep fine particles from drying and plugging the screens. In addition, the screens are cleaned several times each week with a high-pressure washer.

Two of the settling ponds are operated in series and provide storage for the settled material. Supernatant from the settling ponds eventually flows into the final treatment lagoon. Periodically, the waste stream is routed to another pair of settling ponds while solids are allowed to dry. The dewatered solids are then removed and land applied. The two cleaned settling ponds are again brought on-line while the other two are cleaned. The separators were added to the system to reduce the costs of solids management in the four settling ponds.

The final treatment lagoon was originally designed based on anaerobic treatment principles. Surface aerators were added to this pond to provide enough aeration to control odor by maintaining a larger facultative layer.

Mass Balance of the Two-Stage System

After a site visit to the Bos Farm and preliminary analysis of the available data, it was determined that evaluation of system performance would not be as straight-forward as anticipated. A couple of components of the mass balance were either very difficult or impossible to measure without introducing systematic bias. In particular, the volume of water added by the sprayers used to maintain the screens could not be measured, and it was not possible to collect unbiased, representative samples of the flow from the processing pit to the first separator. Therefore, an analysis method was developed to describe system performance using measurable quantities before additional data were collected.

The mass flow of solids (TS, VS) and major plant nutrients (N, P, K) through the two-stage separation process is described by the simple flow diagram given in Figure 2.

The total mass of solids or plant nutrients fed to the system in a day can be calculated as:

$$Q_I [C_I] = m_{R1} [C_{R1}] + m_{R2} [C_{R2}] + Q_O [C_O]. \quad (1)$$

Where,

- Q_I = flow into separator 1, gal/day, (measurement not available),
- $[C_I]$ = concentration of a constituent in separator influent, lb / gal, (measurement not available)
- m_{R1} = mass of the residue removed by separator 1, lb / day,
- $[C_{R1}]$ = concentration of a constituent in residue removed by separator 1, lb / wet lb,
- m_{R2} = mass of the residue removed by separator 2, lb / day,
- $[C_{R2}]$ = concentration of a constituent in residue removed by separator 1, lb / wet lb,
- Q_O = flow from separator 2, gal/day, and

$[C_O]$ = concentration of a constituent in effluent from separator 2, lb / gal.

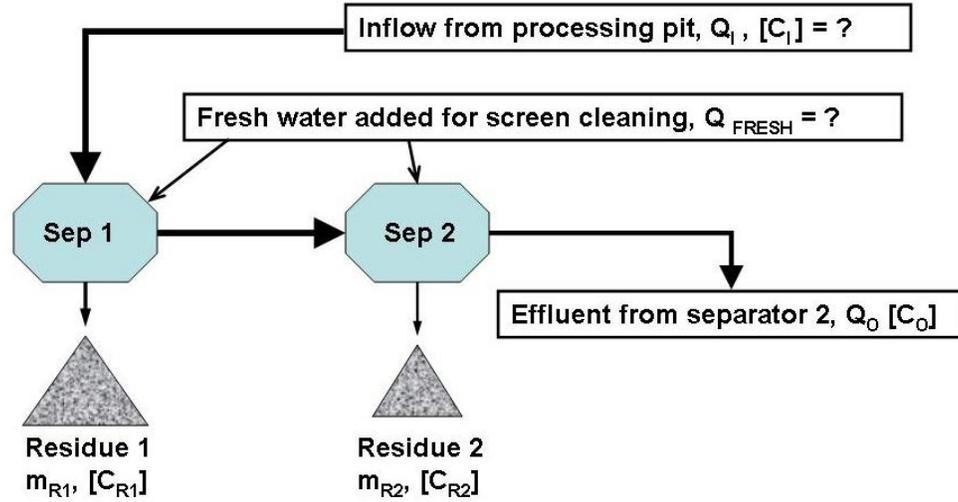


Figure 2. Flow diagram for the two-stage mechanical separation system at Bos Dairy.

Based on the information obtained during a site visit, it was determined that the only components of the mass balance that could be measured accurately were the mass of constituents removed by separator 1 ($m_{R1} [C_{R1}]$), the mass of constituents removed by separator 2 ($m_{R2} [C_{R2}]$), and the mass of constituents remaining in the system effluent ($Q_O [C_O]$). The total mass of any constituent that was fed to the system ($Q_I [C_I]$) can be calculated directly using equation 1.

Mass removal efficiencies were calculated for each of the separators and for the total system. The mass removal efficiency for the entire separation system (MRE_T) was calculated as:

$$MRE_T = 100 (m_{R1} [C_{R1}] + m_{R2} [C_{R2}]) / (m_{R1} [C_{R1}] + m_{R2} [C_{R2}] + Q_O [C_O]). \quad (2)$$

The mass removed by each separator was calculated from the following equations:

$$MRE_{S1} = 100 m_{R1} [C_{R1}] / (m_{R1} [C_{R1}] + m_{R2} [C_{R2}] + Q_O [C_O]), \text{ and} \quad (3)$$

$$MRE_{S2} = 100 m_{R2} [C_{R2}] / (m_{R1} [C_{R1}] + m_{R2} [C_{R2}] + Q_O [C_O]). \quad (4)$$

Data Collected to Evaluate the Two-Stage Separation System

Samples and measurements were taken to quantify the variables shown on the right side of the mass balance given by equation 1.

The total effluent volume, Q_O , was measured on two days in 2007 (Feb. 8th and 9th). Daily flow measurements were obtained using a cumulating magnetic flow meter placed in the effluent pipe at a distance that was over 20 pipe diameters from the second separator. The daily flow value was obtained by averaging these two measurements.

The residue masses, m_{R1} and m_{R2} , were measured for each separator on February 9, 2007 and April 8, 2008. All residues beneath the stacking conveyors from the previous day were removed. After the separation system was operated for 24 hours, all of the solids in each of the residue

piles was loaded into a truck with a loader and the weight of the solids was determined using a certified truck scale. The amount of residue produced by each of the separators per day was the average of the weights obtained on these two days.

Liquid samples were collected from the end of the pipe using a long-handled sampling cup on February 7, 2008. The sampling period consisted of a 1-hour interval during system operation. The multiple samples were combined in a bucket and a well-mixed sample was collected and transported to the DELLAVALLE Laboratory (Fresno, CA) for analysis. The sample was analyzed to determine the concentrations of the following constituents: total solids (TS), fixed solids (FS), volatile solids (VS = TS - FS), total nitrogen (Total-N), ammonium-N, nitrate-N, organic-N (organic-N = Total-N - Ammonium-N - Nitrate-N), total phosphorous expressed as P₂O₅, total potassium expressed as K₂O, and moisture content.

Effluent samples were collected again on April 8, 2008 with a modified procedure. Several samples were collected from the end of the effluent pipe throughout the day. About 4L of effluent sample were placed on ice, transported to US Farm Systems headquarters, frozen, and shipped by overnight courier to Clemson University. After thawing, all samples were combined in a single plastic container. Well-mixed aliquots were drawn from this composite sample for analysis. The sample was analyzed for the same constituents previously mentioned as well as calcium, magnesium, sulfur, and sodium (Na) by the Clemson University Agricultural Services Laboratory.

Samples of the separator residues were collected as the material was being loaded into the truck to be moved or weighed. Samples were collected during the beginning, middle, and end of the loading operation. These smaller samples were mixed and the final composite samples were analyzed to determine composition.

Residue samples were collected on February 7th and 8th in 2007 and on April 8, 2008. The samples collected in February were analyzed by DELLAVALLE Laboratory (Fresno, CA) to determine the concentrations of the following constituents: moisture, TS, FS, VS, Total-N, ammonium-N, P₂O₅, K₂O, Na, and carbon (C).

The residue samples collected in April were stored on ice, frozen, and then shipped by overnight courier to Clemson University. After thawing, samples were analyzed by the Clemson University Agricultural Services Laboratory. The Clemson laboratory provided analyses for the same constituents as the commercial laboratory with the addition of calcium, magnesium, and sulfur.

Gravity Settling Experiment

The effluent from the two-stage separation system flows into settling ponds. The settling ponds store the settleable solids and the supernatant is decanted to the final facultative treatment lagoon. One of the objectives of implementing the two-stage separation system is to remove a large portion of the settleable solids and thereby reduce the costs associated with cleaning sludge from the settling ponds. Therefore, a gravity settling experiment was conducted to provide information to aid in the design of further treatment of the effluent.

An experiment was performed in the laboratory to observe the settling characteristics of the separator effluent sample collected on April 8, 2008. A one-liter graduated cylinder was used to facilitate the measurement of the change in supernatant and settled material volumes with respect to time, observe the final concentrations of solids and plant nutrients in the supernatant, and to observe the interface settling velocity.

The gravity settling experiment was carried out using the following procedure: (1) a well-mixed sample (≈ 1000 mL) of separator effluent was poured into a graduated cylinder, (2) the time when the sample was poured into the cylinder was recorded, (3) the volume of the settled material was measured after 15 and 60 minutes of settling, and (4) at the end of the settling period the supernatant was decanted. The supernatant was analyzed to measure the concentrations of the previously defined plant nutrients, minerals, and solids.

The equations used to describe the effectiveness of gravity settling were derived based on an application of a unit volume mass balance for each of the defined constituents.

Application of the law of conservation of mass on the graduated cylinder used for the settling experiment gave:

$$[C_I] V_I = [C_{SUP}] V_{SUP} + [C_{SET}] V_{SET}. \quad (5)$$

Where,

$$\begin{aligned} [C_I] &= \text{initial concentration of a constituent in the well-mixed separator effluent (g/L),} \\ V_I &= \text{initial mixed volume of the separator effluent (L),} \\ V_{SUP} &= \text{volume of the supernatant layer (L),} \\ [C_{SET}] &= \text{concentration of a constituent in the settled material (g/L), and} \\ V_{SET} &= \text{volume of the settled material (L).} \end{aligned}$$

The mass balance for gravity settling was written on a unit volume basis by dividing through equation 5 by V_I to yield:

$$[C_I] = [C_{SUP}] (V_{SUP} / V_I) + [C_{SET}] (V_{SET} / V_I). \quad (6)$$

The settled volume fraction, SVF, was defined as:

$$SVF = V_{SET} / V_I. \quad (7)$$

The settled volume fraction changes with respect to settling time, and was measured 15 min and 60 min after settling began.

Since all of the volumes in equation 7 were measured, the unit volume mass balance was written in terms of SVF as:

$$[C_I] = [C_{SUP}] (1 - SVF) + [C_{SET}] SVF(t). \quad (8)$$

The only quantity in equation 8 that was not measured after 60 minutes of settling was C_{SET} . Equation 8 was solved for the concentration of a constituent in the settled material to give:

$$[C_{SET}] = \{ [C_I] - [C_{SUP}] (1 - SVF) \} / SVF. \quad (9)$$

The mass of any constituent, C, in the settled material is simply ($[C_{SET}] SVF$). Solving equation 9 for ($C_{SET} SVF$) indicates that the mass fraction removed from the effluent by settling can be written as:

$$MFR_G = \{ [C_I] - [C_{SUP}] (1 - SVF) \} / [C_I]. \quad (10)$$

It also follows that the mass removal efficiency for gravity settling is:

$$MRE_G = 100 MFR_G. \quad (11)$$

The concentration reduction of any constituent (CR_G) by gravity settling was simply:

$$CR_G = 100 \{ ([C_I] - [C_{SUP}]) / [C_I] \}. \quad (12)$$

Since a cylinder was used for the gravity settling experiment, the settled volume fraction is equivalent to the normalized height of the liquid-solid interface and changes with settling time, t as:

$$SVF(t) = V_{SET}(t) / V_I = h(t) / h_I. \quad (13)$$

The rate at which hindered settling occurs was described by the following definition of the interface settling velocity, $U-I$:

$$U-I = [h(t_2) - h(t_1)] / (t_2 - t_1). \quad (14)$$

Where,

- $h(t_1)$ = height of the interface at the beginning of a time step (cm or ft),
- $h(t_2)$ = height of the interface at the end of a time step (cm or ft), and
- $(t_2 - t_1)$ = magnitude of the time step (min or hr).

Other Data Collected

Other information that was gathered either by interviewing the farm owner or by sampling were: the amount of separated solids used for freestall bedding per week, composition of the stall bedding, amount of feed dry matter fed to the cows per day, total feed wastage, average animal weight, seasonality of barn and corral use, flushing schedule, composition of flush water, and composition of the make-up water (supernatant) from the final treatment lagoon.

Results

Results for the Two-Stage Separation System

The composition of the residue collected beneath the two separators is given in Tables 1 and 2. On the average, the residue produced by the first separator (0.020 in) were dryer, higher in carbon, but lower in all major and minor plant nutrients than the residue produced by the second separator (0.010 in). The fact that the residue from the separator with the finer screen (0.010 in) had more total-N (+22%), P_2O_5 (+43%), K_2O (+9%), calcium (+39%), magnesium (+33%), and sulfur (+36%) indicates that these key plant nutrients are more associated with the small particles or are contained in the moisture in the residue. Soluble ammonium-N was 42% higher in the residue from separator 2 as compared to the residue of separator 1 and was attributed to the higher moisture content.

The residue from separator 1 also had a C:N of 26.6 which means it would be a good material for composting without addition of a carbon source. The residue from the second separator could also be used to produce compost, but addition of other waste plant materials to increase the C:N to 25 or more would be desirable.

The high C:N of the residue from separator 2 also indicates that it has the potential to be a net immobilizer of soluble nitrogen in the soil. That is, the break down of the available C in the residue will compete with the plants for available nitrogen. It would be best to compost this material prior to land application or to restrict application to crops with a low demand for nitrogen.

Table 1. Concentrations of solids, plant nutrients, sodium, and carbon in the residue from the first separator (screen opening = 0.020 in).

	Rep 1 ^[a] 2/7/2007	Rep 2 ^[a] 2/8/2007	Rep 3 ^[b] 4/8/2008	Mean	STD	[C _{R1}] Mean
Moisture (%)	76.27%	76.09%	79.40%	77.25%		77.25%
Fraction DM (lb TS/wet lb)	0.2373	0.2391	0.2060	0.2275	0.0186	0.2275
	% dry basis	% dry basis	% dry basis	% dry basis		% wet basis
FS (ash)	6.31	11.59	12.50	10.13	3.342	2.305
VS	93.69	88.41	87.50	89.87	3.342	20.442
Total-N	1.73	1.97	2.11	1.94	0.192	0.441
Ammonium-N	0.11	0.12	0.15	0.12	0.023	0.028
P ₂ O ₅	0.38	0.44	0.55	0.46	0.086	0.104
K ₂ O ₅	0.44	0.58	0.69	0.57	0.125	0.130
Calcium			1.30	1.30		0.296
Magnesium			0.39	0.39		0.089
Sulfur			0.28	0.28		0.064
Na	0.09	0.15	0.14	0.13	0.032	0.029
C	54.48	51.40	46.64	50.84	3.949	11.56
C:N	31.49	26.09	22.10	26.56	4.711	

^[a] Sample analysis by DELLAVALLE Laboratory, Inc., Fresno, CA.

^[b] Sample analysis by Clemson University Agricultural Services Laboratory and Agricultural and Biological Engineering Department, Clemson, SC.

Table 2. Concentrations of solids, plant nutrients, sodium, and carbon in the residue from the second separator (screen opening = 0.010 in).

	Rep 1 ^[a] 2/7/2007	Rep 2 ^[a] 2/8/2007	Rep 3 ^[b] 4/8/2008	Mean	STD	[C _{R2}] Mean
Moisture (%)	78.53%	79.63%	83.66%	80.61%		80.61%
Fraction DM (lb TS/wet lb)	0.2147	0.2037	0.1634	0.1939	0.0270	0.1939
	% dry basis	% dry basis	% dry basis	% dry basis		% wet basis
FS (ash)	13.53	14.27	22.10	16.63	4.749	3.226
VS	86.47	85.73	77.90	83.37	4.749	16.168
Total-N	2.21	2.30	2.60	2.37	0.204	0.460
Ammonium-N	0.135	0.138	0.25	0.17	0.066	0.034
P ₂ O ₅	0.58	0.65	0.75	0.66	0.085	0.128
K ₂ O ₅	0.52	0.52	0.81	0.62	0.167	0.120
Calcium			1.81	1.81		0.351
Magnesium			0.52	0.52		0.101
Sulfur			0.38	0.38		0.074
Na	0.10	0.11	0.17	0.13	0.036	0.024
C	50.28	49.84	44.00	48.04	3.505	9.316
C:N	22.75	21.67	16.92	20.45	3.100	

^[a] Sample analysis by DELLAVALLE Laboratory, Inc., Fresno, CA.

^[b] Sample analysis by Clemson University Agricultural Services Laboratory and Agricultural and Biological Engineering Department, Clemson, SC.

The mass of residue that was produced by the separators on two days is provided in Table 3. On the average, the two separators removed 58,840 lb of dry matter per day (16.34 lb DM/cow or 11.84 lb DM/ 1000 lb live animal weight), and 84% of the dry matter was removed by the first separator.

Table 3. Mass of residue removed by the two separators on two different days.

	Separator 1	Separator 2
Replication 1 (Feb. 2007)		
Mass of solids removed (lb wet/day)	245320	57380
Percent dry matter (lb TS/ wet lb)	23.82	20.92
Dry matter removed (lb TS/day)	58435	12004
Replication 2 (April 2008)		
Mass of solids removed (lb wet/day)	197700	39860
Percent dry matter (lb TS/ wet lb)	20.60	16.34
Dry matter removed (lb TS/day)	40726	6513
Mean		
Dry matter removed (lb TS/day)	49581	9259
Percent dry matter (lb TS/ wet lb)	22.75 ^[a]	19.39 ^[b]
Mass of solids removed (lb wet/day)	217969 ^[c]	47741 ^[c]

^[a] Mean from Table 1.

^[b] Mean from Table 2.

^[c] Calculated from mean dry matter weight and percent dry matter shown.

The concentration data for the effluent from the second separator are given in Table 4. The results from both days were well within the expected day-to-day variation on a commercial farm. The mean of these two data sets provided a good measure of the contents for major plant nutrients and solids. However, minor plant nutrient and sodium data were only available for the sampling day in April 2008.

Table 4. Concentrations of solids, plant nutrients, and sodium in the effluent from the second separator.

	2/7/2007 Rep 1 ^[a] (mg/L)	4/8/2008 Rep 2 ^[b] (mg/L)	Mean (mg/L)	[C _o] (lb/1000 gal)
TS (mg/L)	10300	12006	11153	93.08
FS (mg/L)	3020	3941	3481	29.05
VS (mg/L)	7280	8065	7672	64.03
Total-N	810	932.3	871	7.27
Ammonium-N	15.3	460.1	238	1.98
Organic-N	792.2	460.1	626	5.23
Nitrate-N	2.5	12.0	7.2	0.06
P ₂ O ₅	202.0	288.8	245	2.05
K ₂ O ₅	1016.8	1120.4	1069	8.92
Calcium		427.8	428	3.57
Magnesium		210.9	211	1.76
Sulfur		93.5	93.5	0.78
Na		261.2	261.2	2.18
Moisture (%)	98.97%	98.78%	98.88%	

^[a] Sample analysis by DELLAVALLE Laboratory, Inc., Fresno, CA.

^[b] Sample analysis by Clemson University Agricultural Services Laboratory and Agricultural and Biological Engineering Department, Clemson, SC.

The daily effluent volume ranged from 365,260 to 486,600 gal / day. The average of 425,930 gal / day was used in the mass balance calculations (Table 5).

Table 5. Effluent volume and dry matter remaining in the liquid fraction.

		Effluent Volume, Q_0
Replication 1 (Feb. 8, 2007)		
	Effluent volume (gal/day)	365260
	Solids content (lb TS/gal)	0.0931
	Dry matter remaining (lb TS/day)	33988
Replication 2 (Feb. 9, 2008)		
	Effluent volume (gal/day)	486600
	Solids content (lb TS/gal)	0.0859
	Dry matter remaining (lb TS/day)	41799
Mean		
	Effluent volume (gal/day)	425930
	Solids content (lb TS/gal)	0.0931 ^[a]
	Dry matter remaining (lb TS/day)	39633

^[a] Mean from Table 4.

The mean residue masses, effluent volume, and the corresponding constituent concentrations were used to compute the components of the mass balance as defined by equation 1. Based on these values the mass removal efficiencies for the two-stage system as well as each separator were calculated (equations 2, 3 and 4). The results are given in Table 6.

Table 6. Mass of solids and plant nutrients fed to and removed by the two-stage separation system.

	S1	S2	Effluent	INPUT	S1	S2	(S1 + S2)
	$m_1[C_{R1}]$	$m_2[C_{R2}]$	$Q_0[C_0]$	(S1+S2+Eff)	MRE_{S1}	MRE_{S2}	MRE_T
	lb/day	lb/day	lb/day	lb/day	(%)	(%)	(%)
TS (dm)	49581	9259	39644	98483	50.3	9.4	59.7
FS (ash)	5024	1540	12372	18936	26.5	8.1	34.7
VS	44557	7719	27272	79547	56.0	9.7	65.7
Total-N	960	219	3096	4276	22.5	5.1	27.6
Ammonium - N	62	16	845.0	923	6.7	1.7	8.4
P ₂ O ₅	226	61	872.2	1160	19.5	5.3	24.8
K ₂ O ₅	283	57	3798.3	4138	6.8	1.4	8.2
Na	62.8	11.7	928.5	1003	6.3	1.2	7.4
C	25206	4448	NM	NA	NA	NA	NA
Calcium	645	168	1521	2333	27.6	7.2	34.8
Magnesium	193	48	750	991.1	19.5	4.9	24.4
Sulfur	139	35	332	506.2	27.4	6.9	34.4

The two-stage separation system removed 59.7% of the dry matter from the manure stream and 65.7% of the volatile solids (VS). The majority of the solids removal was accomplished by the first separator with the second screen providing only 9.4% removal of TS and 9.7% removal of VS.

The total system was able to remove 27.6% of the total-N, 24.8% of the phosphorous, and 24.4% to 34.8% of the magnesium, sulfur, and calcium. Only small amounts of the soluble constituents

(ammonium-N, potassium, and sodium) were removed by screening as expected. The small amounts of soluble constituents removed were contained in the moisture of the residues. These results indicate that two thirds to three quarters of the nitrogen, phosphorous, calcium, magnesium, and sulfur was contained in the particles that passed through a 0.010” (0.254 mm) screen or in the liquid. This agrees with many previous studies that demonstrated that plant nutrients in dairy manure are mostly associated with fine particles or are contained in solution (e.g. Meyer, et al., 2007; Wright, 2005; Zhang and Westerman, 1997).

During the time period that this study was conducted the milking herd size averaged 3600 cows. The average weight per cow was 1380 lb. Therefore, the average production live weight was 496,800 lb or 4968 animal units (1 AU = 1000 lb). The mass balance results are given on an animal unit basis in Table 7. These data can be used to assist in the design of sedimentation basins, lagoons, or covered lagoon digesters for different herd sizes that have the same type of two-stage separation system.

Table 7. Mass of solids and plant nutrients fed and removed per animal unit (1 AU = 1000 lb average live weight, AU = 4968).

	Mass IN lb / AU-day	Total Mass Removed lb / AU-day	Mass Remaining in Liquid lb / AU-day
TS (dm)	19.82	11.84	7.98
FS (ash)	3.81	1.32	2.49
VS	16.01	10.52	5.49
Total-N	0.861	0.237	0.623
Ammonium - N	0.186	0.016	0.170
P ₂ O ₅	0.233	0.058	0.176
K ₂ O ₅	0.833	0.068	0.765
Na	0.20	0.015	0.187
C	NA	5.97	NA
Calcium	0.4695	0.1635	0.3061
Magnesium	0.1995	0.0486	0.1509
Sulfur	0.1019	0.0350	0.0669

The data indicate that 19.82 lb of total solids per AU were present in the manure stream that was treated by the separation system each day. The volatile solids composed 80.7% of the dry matter.

Based on an interview with the owner it was estimated that about 384,000 lb of dried residue from separator 1 was used for freestall bedding per week. The moisture content of the bedding ranged from 10% to 15%. If a bedding moisture content of 12% is assumed, the amount of bedding used was 9.7 dry pounds per AU per day. The owner also indicated that the cows were fed 50 lb of feed dry matter per day and farm records indicated that feed wastage was small at 2%. Therefore, feed wastage did not appear to be a large source of dry matter in the flushed manure. Assuming that the cows produce 14.4 lb of manure dry matter per AU per day gave an expected solids production of 24 lb TS/AU-day (14.4 + 9.7 lb DM/AU-day). Therefore, the solids fed the separation system were 21% lower than expected. However, freestall bedding use is difficult to accurately measure.

This study was conducted during the cool part of the year when the cows were kept in total confinement. During the interview with the owner it was also determined that during the hot summer months the milking cows are given free access to outside corrals for seven to eight hours

each night. Therefore, up to one third of the manure in the freestall barns will not be collected and the loading on the manure treatment system will be reduced. Almost all of the cows take advantage of the outside corral part of this time, but it was difficult to precisely quantify the actual amount of manure that would not be conveyed to the treatment system. The best way to quantify this seasonal difference would be to collect additional data during the hot season.

Results for the Gravity Settling Experiment

A well-mixed 960 mL sample of effluent from the second separator was poured into a 1L graduated cylinder. The volume of the settled material was measured after 15 and 60 minutes. At the end of 15 minutes the volume of the settled material was determined to be only 80 mL using a scale for depths below the 100 mL graduation. At the end of 60 minutes the settled volume was estimated to be 70 mL. Next, about 500 mL of supernatant was slowly decanted and kept for analysis. The remaining supernatant and settled solids were mixed and poured into a 500 mL graduated cylinder to increase the accuracy of the final settled volume measurement. The solids were allowed to settle again for another hour and the settled volume was again found to be 70 mL. The remaining supernatant was decanted slowly and added to the previous 500 mL. The results, including the interface heights, interface settling velocities, and the settled volume fractions, are given in Table 8.

Table 8. Change in settled volume and liquid-solid interface height with respect to settling time.

Elapsed Time (min)	Volume of Settled Material (mL)	Liquid-Solid Interface Height (cm)	Interface Settling Velocity, $U-I$ (ft/hr)	Settled Volume Fraction, SVF(t)
0	960	29.446	--	1.0
15	80	2.454	-3.542	0.083
60	70	2.147	-0.013	0.073

The solids in the separator effluent settled rapidly as indicated by the initial interface velocity of 3.542 ft/hr. After 60 minutes the settled solids occupied only 7.3% of the total volume of the separator effluent. This volume will decrease very slowly as the solids thicken by compression settling at the rate of 0.013 ft/hr or less.

The supernatant was analyzed for the same constituents as the separator effluent. The data for the initial well mixed sample and the supernatant after 60 minutes of settling are compared in Table 9 using the concentration reduction for each constituent.

The CR_G values were either negative or below 5% for the four soluble constituents. This is common for gravity settling experiments since soluble constituents cannot be removed by settling. The negative or low CR_G values indicate that the initial and supernatant concentrations for these constituents were not impacted by settling. Therefore, it was more accurate to use the average concentration for these constituents as indicated in the table.

Since organic-N was calculated from independent measurements of total-N, ammonium-N, and nitrate-N the concentrations were corrected using the mean concentrations for ammonium and nitrate nitrogen. The corrections are shown in Table 10.

If the initial and supernatant concentration of a constituent is the same then equation 11 simplifies to: $MFR_G = SVF(60 \text{ min})$.

Table 9. Initial and final constituent concentrations for the settling experiment.

Constituent	Initial Concentrations (mg/L)	Final Supernatant Concentrations (mg/L)	Concentration Reduction (%)	Mean Concentrations of Soluble Constituents (mg/L)
TS	12006	9256	22.9	
VS	8065	6098	24.4	
Ammonium - N	460.1	450.5	2.1	455.3
Organic-N	460.1	370.3	19.5	
Nitrate-N	12.0	13.2	-10.0	12.6
TN	932.3	834.0	10.5	
P ₂ O ₅	288.8	215.7	25.3	
K₂O	1120.4	1179.1	-5.2	1149.7
Calcium	427.8	341.5	20.2	
Magnesium	210.9	180.9	14.2	
Sulfur	93.5	85.1	9.0	
Sodium	261.2	276.8	-6.0	269.0

Table 10. Corrected organic nitrogen concentrations for gravity settling.

Form of Nitrogen	Initial Concentrations (mg/L)	Final Supernatant Concentrations (mg/L)	Concentration Reduction (%)
TN	932.3	834.0	10.5
Ammonium - N	455.3	455.3	0
Nitrate-N	12.6	12.6	0
Organic-N = (TN - Am-N - Nitrate-N)	427.0	366.1	14.3

The mass balance results for the gravity settling experiment are given in Table 11. The results indicate that 28.5% of the TS and 29.9% of the VS can be removed by sedimentation after passing the manure stream through a 0.020 in and a 0.010 in screen. The removal of phosphorous (P₂O₅) was about the same as the VS removal. Comparison of the gravity settling mass removal efficiencies with the results for the second separator (Table 6) indicates that gravity settling of the separator effluent was more effective than the second separator. However, the disadvantage of gravity settling is that the settled material is slurry and not a stackable solid.

These gravity settling results can assist in the design of a covered lagoon digester. Settling will occur in a covered lagoon and non-degradable, inert sludge will build-up over time. The portion of the settled material that will eventually become inert sludge was estimated as:

$$M_{SL} = [(1-F_{VSD}) MVS_{SET} + MTS_{SET} - MVS_{SET}] \theta. \quad (15)$$

Where,

- M_{SL} = mass of settled material that will become inert sludge,
- F_{VSD} = fraction of VS destroyed over the specified time period,
- MVS_{SET} = mass of VS that settles,
- MTS_{SET} = mass of TS that settles, and
- θ = sludge storage period in days.

Table 11. Mass balance results for gravity settling of effluent from the two-stage screening process.

Constituent	Initial Mass [C _I] V _I (mg)	Supernatant Mass [C _{SUP}] V _{SUP} (mg)	Settled Mass [C _{SET}] V _{SET} (mg)	Mass Removal Efficiency (%)
TS	11526	8238	3288	28.5
VS	7742	5427	2315	29.9
Ammonium - N	437	405	32	7.3
Organic-N	410	326	84	20.5
Nitrate-N	12	11	1	7.3
TN	895	742	153	17.1
P ₂ O ₅	277	192	85	30.8
K ₂ O	1104	1023	80	7.3
Calcium	411	304	107	26.0
Magnesium	202	161	41	20.5
Sulfur	90	76	14	15.6
Sodium	258	239	19	7.3

Based on a review by Chastain (2006), the value of F_{VSD} for dairy manure that has not received primary treatment is 0.59 provided the settled solids remain in a lagoon for five years or more. For a sludge retention time of six months F_{VSD} is on the order of 0.44.

It must be emphasized that these values of F_{VSD} were for unscreened manure. Screening manure prior to biological treatment will remove many of the very slow to degrade volatile solids. As a result, the value of F_{VSD} for separator effluent would be greater than for unscreened manure.

The VS in swine manure is more degradable since bedding is not used in the housing area and the ration fed is predominately ground grains and not forage. Consequently the value of F_{VSD} for swine manure is about 0.81 for retention times of one year or more.

It is expected that screened dairy manure will have a F_{VSD} between 0.59 and 0.81, but the value is unknown at the present. The value of F_{VSD} for screened dairy manure was assumed to be 0.65. Using this value in equation 15 with the data from this experiment indicates that 1783 mg of the settled solids would be inert sludge in a covered lagoon. Therefore, about 54% of the mass of settleable solids on the separator effluent will become inert sludge.

The volume occupied by the inert sludge layer depends on the concentration of TS in the sludge layer after several years. The volume of the sludge layer was calculated as:

$$V_{SL} = M_{SL} / [TS_{SL}] \quad (16)$$

Where,

$$V_{SL} = \text{volume of the sludge layer, and}$$

$$[TS_{SL}] = \text{the concentration of the TS in the sludge layer.}$$

The recommended value for $[TS_{SL}]$ is 127 g/L (7.93 lb TS/ft³) based on a review provided by Chastain (2006). The standard deviation about this mean was 33.3 g/L which corresponds to a coefficient of variation of 26%.

Based on the data from the separation system at Bos dairy and the settling experiment, the sludge production in a covered lagoon digester following the two-stage separation system was estimated to be 0.155 ft³ / AU-day. If primary treatment was not provided the sludge production would be

0.556 ft³ / AU-day based on the model presented by Chastain (2006). Therefore, the two-stage separation system is projected to reduce long-term sludge build-up in a covered lagoon by 72%.

A covered lagoon is the primary anaerobic digester option considered for dilute waste streams on dairy farms at the present. Furthermore, the loading rate of a digester is typically limited due to the large volume of water. In many municipal waste treatment systems, only the settled material from a clarifier is fed to the anaerobic digester in order to more optimally load the digester and to reduce digester size and cost.

The data from the gravity settling experiment were used to calculate the concentrations of solids and plant nutrients in the settled material using equation 9. The calculated concentrations are given in Table 12.

Table 12. Concentrations of solids and plant nutrients in the settled material (calculated using equation 9).

Constituent	Settled Material Concentration	
	mg/L	$[C_{SET}] / [C_i]$
TS	46,970	3.91
VS	33,070	4.10
Ammonium - N	455	1.0
Organic-N	1202	2.81
Nitrate-N	13	1.0
TN	2182	2.34
P ₂ O ₅	1218	4.22
K ₂ O	1150	1.0
Calcium	1525	3.56
Magnesium	592	2.81
Sulfur	200	2.14
Sodium	269	1.0

Settling increased the concentration of TS and VS by a factor of 4 and the volatile solids fraction of the settled material was 0.70. Therefore, gravity settling could be implemented to reduce the volume to be treated by an anaerobic digester by 92% and to increase the concentration of VS by 310%. The liquid fraction could be treated by facultative lagoon, high-rate anaerobic digestion, or a re-circulating aerobic trickling filter. There are many other options that could be considered, but a complete discussion is beyond the scope of this report.

Composition of Freestall Bedding

The residue from the first separator was treated by spreading it out in layers in the space between the freestall barns. Periodically, the solids were mixed by disking to enhance drying and to promote exposure of the material to solar radiation. The dried material was stored in windrows and was used for stall bedding.

A grab sample of bedding material was analyzed to provide an estimate of the effects of the drying process. The moisture content and the concentrations of solids and plant nutrients are compared with fresh residue from the first separator in Table 13.

Table 13. Comparison of residue from the first separator with the dried solids used for freestall bedding.

	Residue from Separator 1 ^[a]	Freestall Bedding ^[b]
Moisture (%)	77.25%	9.24%
Fraction DM (lb TS/wet lb)	0.2275	0.9076
	% dry basis	% dry basis
FS (ash)	10.13	24.59
VS	89.87	75.41
Total-N	1.94	2.57
Ammonium-N	0.12	0.06
P ₂ O ₅	0.46	0.83
K ₂ O ₅	0.57	2.13
Calcium	1.30	2.09
Magnesium	0.39	0.61
Sulfur	0.28	0.46
Na	0.13	0.20
C	50.84	39.01
C:N	26.56	15.18

^[a] Means from Table 1.

^[b] Grab sample collected on 4/8/2008.

The drying process was very effective as indicated by a drop in moisture content from 77.25% to 9.24%. Also, most of the organic constituents became more concentrated, that is the dry matter concentrations increased, as would be expected for any drying process. Therefore, the drying process conserved most of the plant nutrients and sodium and these nutrients were recycled back to the manure stream by being used as freestall bedding.

The only constituents that were lost during the drying process were ammonium-N and carbon. Fifty percent of the ammonium-N was lost to the atmosphere by ammonia volatilization. Carbon was reduced by 23%. It is believed that this fraction of carbon was utilized by microbes and was lost as CO₂ by respiration. As a result, the C:N was reduced by 43% even though the material was not intentionally composted. Therefore, the drying process resulted in a significant loss of N and C from the farm.

Composition of Make-Up Water from the Final Lagoon

A grab sample was also collected to determine the amount of solids and plant nutrients contained in the recycled water. The results are compared with the mean separator effluent composition in Table 14.

The percent differences in concentration between the effluent and the make-up water indicate that the settling pond and final lagoon was adding soluble nitrogen (ammonium-N and nitrate-N), total-N, potassium (K₂O), and sodium to the treated effluent. That is, the pond and lagoon system was a source of these nutrients. Furthermore, the comparison of the tabulated values of Δ[C] with the results of the settling experiment (Table 9 and 11) indicated that settling was the primary mode of treatment provided by the pond and lagoon system for all other constituents except VS, organic-N, and sulfur.

Table 14. Comparison of separator effluent composition with a grab sample of the make-up water from the final lagoon.

Constituent	Effluent From S2, [C] ^[a] (mg/L)	Water added to recycle pit from final lagoon [C] ^[b] (mg/L)	Δ[C] (%)
TS	11153	7880	29
VS	7672	4240	45
Ammonium - N	238	570	- 139
Organic-N	626	340	46
Nitrate-N	7.2	9.6	- 33
TN	871	920	- 5.6
P ₂ O ₅	245	209	15
K ₂ O	1069	1322	- 24
Calcium	428	349	18
Magnesium	211	185	12
Sulfur	94	55	41
Sodium	261	312	- 20

^[a] Means from Table 4.

^[b] Grab sample collected on April 8, 2008.

The source of the additional soluble plant nutrients was the decomposing solids that were loaded into the settling ponds and treatment lagoon before the two-stage separation system was implemented.

Sodium and potassium (K₂O) are two soluble constituents that were 20% and 24% higher in the make-up water than in the separation system effluent. These nutrients were added to the system long before the separation system was implemented. They can only be removed from the system by way of the separated solids and by irrigating lagoon supernatant onto cropland based on its fertilizer value. Since the lagoon supernatant is being used to fertilize nearby cropland these concentrations are expected to decrease over time.

The biological and chemical transformations of nitrogen in a pond and lagoon system are very complex. The 139% increase in ammonium-N was the result of organic-N mineralization. Overtime, microbes in the lagoon will breakdown the organic-N to ammonium-N. Organic-N associated with fine particles will mineralized quickly. However, organic-N in the settled material will tend to be released slowly into the water column. Therefore, the large increase in ammonium-N was the result of high solids loading in the past. A portion of the ammonium-N will convert to ammonia-N and will be lost from the lagoon and pond surfaces by volatilization. The rate at which this occurs is dependant on temperature, and pH. If significant amounts of dissolved oxygen are available, a portion of the ammonium will be converted to nitrate. Oxygen can be transferred to the surface at low rates by wind action, but in this case surface mechanical aerators were used. The effect of aeration explains the 33% increase in nitrate-N. The organic-N was observed to drop by only 46% as compared to an increase in ammonium-N of 139% and of nitrate-N by 33%. These results also point to the conclusion that manure added from previous years was adding to the nutrient content of the water column in the final lagoon. In contrast to these results, the total-N increased by only 5.6%. It is believed that losses of N by ammonia volatilization are the explanation for this modest increase in total-N. If volatilization had not occurred the increase in total-N would have been larger.

Over time the concentrations of all forms of N is expected to decrease as implementation of the separation system and irrigation of lagoon supernatant continues to remove plant nutrients from the system. The other practice that should decrease plant nutrient concentrations is removal of solids from the settling ponds.

Composition of Flush Water from the Processing Pit

A grab sample was collected of the processing pit water that was used to flush the freestall alleys. The composition of the flush water is compared with the composition of the make-up water in Table 15. The results indicate that much of the dry matter (TS), ammonium-N, nitrate-N, K, and sodium in the flush water were recycled from the final lagoon. Overtime, the concentrations in the flush water are expected to decrease as solids, minerals, and plant nutrients are removed by the two-stage treatment system and irrigation.

Table 15. Comparison of flush water composition with the make-up water from the final lagoon.

Constituent	Flush Water, [C] ^[a] (mg/L)	Water added to recycle pit from final lagoon [C] (mg/L)	Δ [C] (%)
TS	10390	7880	24
VS	7262	4240	42
Ammonium - N	460	570	- 24
Organic-N	370	340	8
Nitrate-N	6.0	9.6	- 60
TN	836	920	- 10
P ₂ O ₅	218	209	4
K ₂ O	978	1322	- 35
Calcium	332	349	- 5
Magnesium	169	185	- 9
Sulfur	74	55	26
Sodium	233	312	- 34

Conclusions

1. The US Farm System two-stage separation system was able to remove 59.7% of the TS, and 65.7% of the VS from flushed dairy manure. However, two thirds to three quarters of the nitrogen, phosphorous, calcium, magnesium, and sulfur remained in the separator effluent. These results agree with other studies that have demonstrated that the majority of the plant nutrients in dairy manure are contained in fine particles or in the liquid fraction.
2. The majority of the solids and plant nutrients that were removed by the two-stage system were removed by the first separator.
3. The separation system effluent contained 11,153 mg TS/L of which 68.8% was volatile solids. Nitrogen was the predominate major plant nutrient in the effluent followed by K₂O and then P₂O₅. Therefore, the separator effluent would be a good organic fertilizer for many crops and still has a significant potential for methane production in an anaerobic digester.
4. The results of the settling experiment on the system effluent indicated that 28.5% of the TS and 29.9% of the VS can be removed from the liquid fraction by sedimentation. Settling occurred rapidly with an initial interface settling velocity of 3.54 ft/hr. Once the settled

material occupied 8.3% of the initial effluent volume the settling rate slowed to 0.013 ft/hr. The final volume of the settled material was 7.3% of the effluent volume (72.9 mL/L). It was estimated that 54% of the settleable solids in the separation system effluent would become inert sludge in a covered lagoon digester. It was also estimated that the two-stage separation system would reduce inert sludge build-up in a covered lagoon digester by 72%. Application of gravity settling would facilitate more efficient loading of an anaerobic digester since the concentration of VS in the sediment was increased by a factor of 4 and the treatment volume could be reduced by about 92%. The supernatant could also receive treatment in either high-rate or low rate digesters.

5. The residues from both of the separators in the two-stage system were dry enough to store and handle as a solid. The C:N of the residue from the first separator was 26.6 with a moisture content of 77.25%. With a small amount of drying, this material would be an excellent substrate for composting. The C:N of the second residue was 20.5 with a moisture content of 80.6%. This material would also be an excellent material for composting, but additional dry carbon is needed to increase the C:N and reduce the moisture content. The high C:N of the residue from the second separator would cause it to be a net immobilizer of nitrogen if land applied without composting.
6. The residue from the first separator was dried and recycled as freestall bedding. The drying process was found to be effective since the moisture content was decreased from 77.25% to 9.24%. During the drying process 50% of the ammonium-N was lost to the atmosphere by ammonia volatilization. Twenty-three percent of the carbon was also lost and was attributed to microbial respiration.

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