

FINAL

**A Characterization of Transformations Occurring
As Swine Manure Accumulates in Deep Pits**

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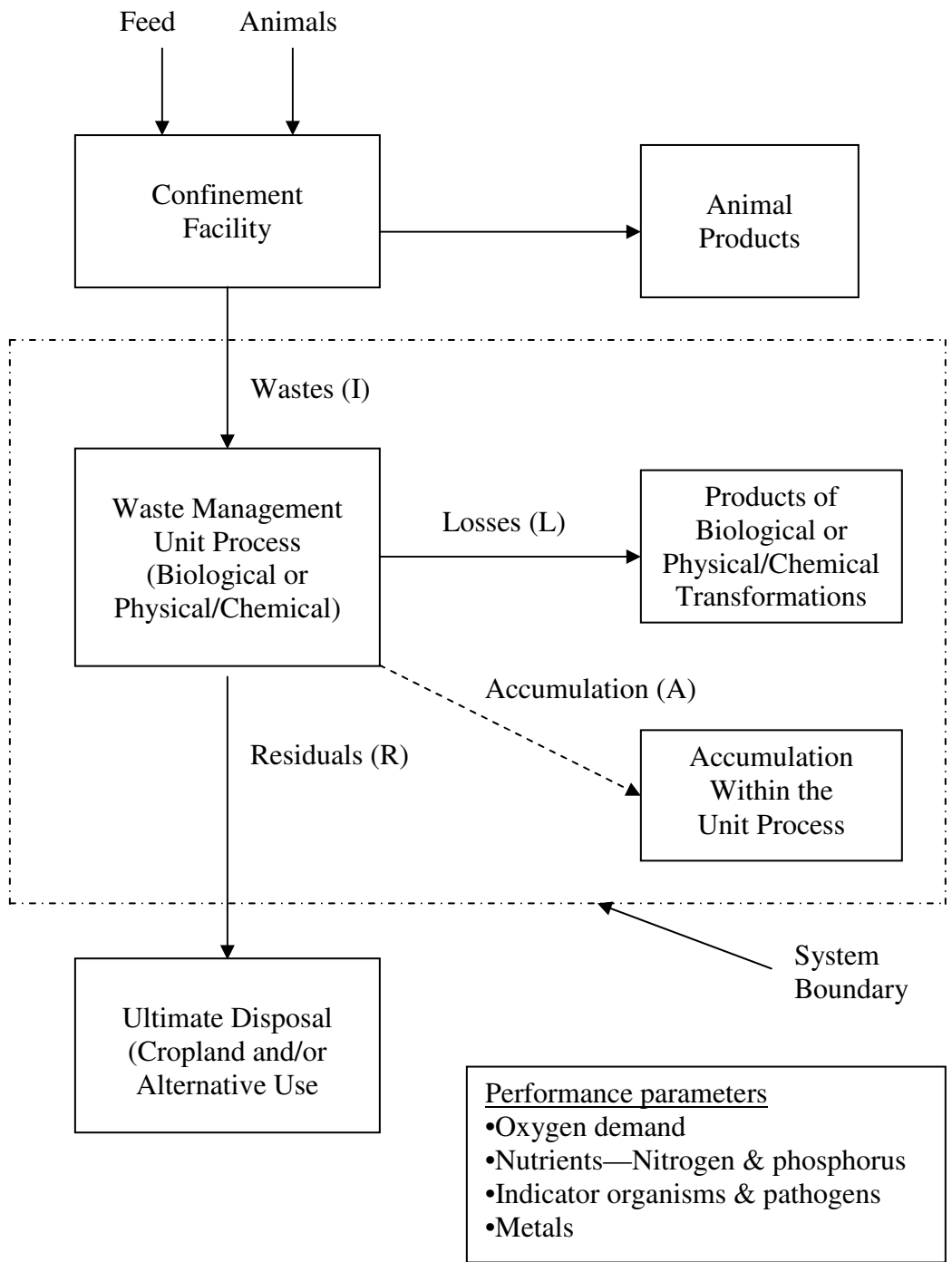
July 30, 2003

EPA Contract #68-W7-0068
Task Order 4017

PREFACE

This report summarizes the results from one of a series of studies designed to: 1) more fully characterize and quantify the protection of air and water quality provided by waste management systems currently used in the swine and dairy industries and 2) delineate associated costs. The overall objective of this effort is to develop a better understanding of: 1) the potential of individual system components and combinations of these components to ameliorate the impacts of swine and dairy cattle manures on environmental quality and 2) the relationships between design and operating parameters and the performance of the biological and physical/chemical processes involved. A clear understanding of both is essential for the rational planning and design of these waste management systems. With this information, swine and dairy producers and their engineers as well as the regulatory community will have the ability to identify specific processes or combinations of processes that will effectively address air and water quality problems of concern.

The following schematic illustrates the comprehensive mass balance approach that is being used for each unit process in these performance evaluations. When a system is comprised of more than one unit process, the performance of each process is characterized separately. Then the results are aggregated to characterize overall system performance. This is the same approach commonly used to characterize the performance of domestic and industrial wastewater treatment and chemical manufacturing unit processes. Past characterizations of individual process and systems performance frequently have been narrowly focused and have ignored the generation of side streams of residuals of significance and associated cross media environmental quality impacts. A standardized approach for cost analysis using uniform boundary conditions also is a key component of this comparative effort.



Where: $L = I - (R + A)$
 (I and R are measured and
 L and A are estimated)

Figure 1. Illustration of a standardized mass balance approach to characterize the performance of animal waste management unit processes.

SECTION 1

SUMMARY AND CONCLUSIONS

The objectives of this study were to: 1) characterize the physical and chemical transformations that occur as swine manure accumulates in deep pits under slatted floors and 2) use this information to assess the performance of this swine manure management system with respect to emissions of methane, ammonia, and hydrogen sulfide and parameters that potentially effect water quality.

The study was conducted at a commercial swine grow-finish operation located near Ames, Iowa. Manure accumulating in a deep pit under a slatted floor in one of the three finishing units located on this farm was sampled at approximately two-week intervals over two consecutive grow-finish cycles, which comprised approximately nine months. Each sample collected, which was a composite of three vertically integrated sub-samples, was analyzed to determine concentrations of total solids (TS), total volatile solids (TVS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH₃-N), total phosphorus (TP), total sulfur (S), sulfur as sulfides, arsenic, copper, zinc, fecal coliforms (FC), fecal streptococcus (FS), and pH. The volume of manure accumulated also was determined to allow construction of material balances, which characterize transformations and losses by comparing the mass of each parameter in the accumulated manure with the estimated mass excreted. The performance, feed conversion efficiency, and rate of weight gain of each group of feeder pigs also was determined based on records of feed consumed and initial and final average live weights.

Emissions

During the two feeder pig grow-finish cycles that occurred during this study, results of materials balances indicate that 30,540 lb of methane, 965 lb of hydrogen sulfide, and 6,193 lb of ammonia was emitted as manure accumulated in a deep under a slatted floor. The methane emitted was estimated based on the observed reduction in COD, which was 43.6 percent with a corresponding observed reduction in TVS of 40.0 percent. In a previous evaluation of the performance of a mixed mesophilic anaerobic digester on a farrow-to-wean operation, reductions in COD and TVS were 68.8 percent and 64.0 percent, respectively (Martin, 2003). This suggests partial

anaerobic stabilization of swine manure occurs in deep pits without the benefit of using the methane produced as a source of energy. In this study, an estimated 29.7 percent of excreted nitrogen was lost via ammonia volatilization. In comparison, Martin (2002) previously reported a loss of 56 percent from a single cell anaerobic lagoon used for swine waste stabilization. Therefore, it appears that deep pits are more effective than anaerobic lagoons in reducing ammonia emissions and conserving swine manure nitrogen. However, ammonia emissions from sites used for land application of manure from deep pits will be if manure is not immediately incorporated into the soil, given that almost 75 percent of the nitrogen present is as ammonia nitrogen. In Table 1-1, the emissions of methane, hydrogen sulfide, and ammonia are presented on a per pig finished and per 1,000 lb of weight gain basis.

Table 1-1. Summary of estimated emissions of methane, hydrogen sulfide, and ammonia that occur from deep pits used for the collection and storage of feeder pig manure.

Emitted Compounds	Lb per pig finished	Lb per 1,000 lb of weight gain
Methane	12.9	58.6
Hydrogen sulfide	0.41	1.85
Ammonia	3.2	14.2

Water Quality Impacts

The reductions in COD and TKN that occurred as swine manure accumulated in a deep pit were substantial: 43.6 percent and 29.7 percent, respectively. Therefore, deep pit systems offer some reduction in the potential impact to surface waters adjacent to land application sites. However, the potential impact could still be substantial, given the remaining readily biodegradable fraction of organic compounds and nutrients present. Although the observed reductions in the densities of FC and FS are substantial, these reductions are not significant given the magnitudes of the

densities of these microorganisms remaining. Thus, it seems reasonable to assume that any concurrent reduction in pathogens present also would not be significant.

SECTION 2

INTRODUCTION

Deep pits located under slatted floors commonly are used in the swine industry for manure collection and storage especially in colder climates, such as the upper Midwest. In cold climates, achieving satisfactory performance of an aerobic lagoon can be difficult. Unlike anaerobic lagoons, deep pits are not intended to provide waste stabilization and the reduction of potential water quality impacts through the microbially mediated reduction of complex organic compounds to methane and carbon dioxide. However, manure accumulating in deep pits does provide a suitable environment for anaerobic microbial activity. Therefore, deep pits will emit methane, ammonia, and a variety of reduced sulfur compounds, including hydrogen sulfide. In addition, deep pits, unlike properly designed and managed anaerobic lagoons, can emit a variety of volatile organic compounds (VOCs) that are the products of the incomplete reduction of complex organic compounds to methane. Many of these VOCs are products of the incomplete degradation of excreted proteinaceous compounds and are responsible, in part, for the objectionable odors typically associated with swine and other animal manures. The emission of a substantial amount of VOCs is not necessary to create a significant odor problem.

Objectives

The objectives of this study were to characterize the physical and chemical transformations that occur as swine manure accumulates in deep pits under slatted floors and to use this information to assess the performance of this swine manure management system with respect to emissions of methane, ammonia, and hydrogen sulfide and manure characteristics that potentially affect water quality.

SECTION 3

METHODOLOGY

Study Site

The site for this study was a commercial swine finishing operation located approximately 10 miles northwest of Ames, Iowa. This farm is a contract finishing operation for Swine Graphics, Webster City, Iowa and has three identical 1,000 head nominal capacity finishing units with wet/dry feeding systems and tunnel ventilation systems. Each unit is operated on an “all-in-all-out” basis. All manure that is collected in the deep pits is applied to land used for corn and soybean production. On this farm, the deep pits typically are emptied in the spring before crops are planted and in the fall after crops are harvested. The volume of each pit is 91,692 ft³ (685,948 gal) at a maximum manure depth of nine feet. Only one of the three finishing units, Building No. 3, was used for this study.

Study Chronology

Sample and other data collection at Building No. 3 commenced on January 7, 2002 with the housing of the first of two groups of feeder pigs finished during the study and ended with the sale of the second group of pigs finished on October 23, 2002. In preparation for this study, most of the accumulated manure from previous production cycles was removed. It was not possible to remove all of the manure present and 26 inches (22,074 ft³) remained in the pit at the beginning of the study. Table 3-1 provides details of the two production cycles that occurred during the study.

Sample and Other Data Collection

Sample collection began on January 11, 2002 and continued at approximately two-week intervals through October 23, 2002, when the second production cycle was completed. Each sample analyzed was a composite of three vertically integrated sub-samples collected at spatially diverse locations within the deep pit. The same sampling locations were used throughout the study.

Each sub-sample was collected using a 1.5-inch diameter polyvinyl chloride (PVC) tube inserted vertically into the column of the accumulated manure. When the tube reached the floor of the pit, it was lifted slightly to allow closure by pulling on a cable threaded through the tube and attached to a two-inch rubber ball. The sub-samples then were combined and mixed until a uniform mixture was obtained, and then a composite sample was withdrawn for analysis. Each composite sample was immediately cooled to approximately 4 °C and delivered for analysis within 24 hours of collection.

Other data collected included the ambient air temperature outside of Building No. 3, the temperature of the air above the accumulating manure in the deep pit, and the temperature of the accumulated manure in the pit. The producer provided the production data necessary to characterize animal performance for each of the two groups of pigs finished during the study. These data included number and average live weight of pigs housed and sold, and the feed consumption for each production cycle. In addition, the integrator provided a proximate analysis of each ration fed during the study.

Analytical Methods

Each composite sample was analyzed by Minnesota Valley Testing Laboratories, Inc., Nevada, Iowa for the physical, chemical, and microbiological parameters listed in Table 3-2 using the analytical methods indicated.

Data Analysis

For each parameter of interest, the results of the analyses of the composite samples of the accumulated manure were analyzed statistically for the possible presence of extreme values or outliers using Dixon's criteria for testing extreme observations in a single sample (Snedecor and Cochran, 1980). If the probability of the occurrence of a suspect observation based on order statistics was less than five percent ($P < 0.05$), the suspect observation was considered an outlier and not included in subsequent statistical analyses.

The results of the analyses of the composite samples were analyzed to determine if the observations were normally distributed by comparing mean and median values and by the

Kolmogorov-Smirnov One-Sample Test (Steel and Torrie, 1980). Lognormal distributions were assumed for the densities of fecal coliforms (FC) and fecal streptococcus (FS).

Performance Evaluation

This study characterized (1) the physical and chemical transformations that occur as swine manure accumulates in deep pits under slatted floors, and (2) the associated emissions of methane, ammonia, and hydrogen sulfide. These parameters were evaluated using a materials balance approach by comparing estimates of the mass of manurial constituents excreted to the mass of constituents remaining in the pit at the end of the study. As noted above, 18 composite samples of the manure accumulating in deep pit were collected and analyzed during the study's two production cycles to characterize the composition of the manure that accumulated.

Because this study was conducted at a commercial swine grow-finish operation, it was not possible to collect urine and feces from individual animals or a group of animals to determine rates of excretion and the quantities of the various manurial constituents of interest entering the deep pit during the period of the study. Therefore, it was necessary to use suggested typical rates of excretion as the basis or nutritional considerations for estimating these quantities. Both the U.S. Department of Agriculture (1992) and the American Society of Agricultural Engineers (2001) have published these standard reference values on a lb per 1,000 lb live weight-day basis for various constituents of swine and other livestock and poultry manures. The rationale for selecting the excretion rate for each manurial constituent of interest to estimate the quantity of that constituent excreted and to characterize subsequent transformation and loss is described later in the results and discussion section of this report.

SECTION 4

RESULTS AND DISCUSSION

Animal Performance

As shown in Table 4-1, the performance of both groups of pigs finished during the study was not atypical. As indicated in Table 3-1, the first production cycle started during the winter and ended in the early spring whereas the second occurred during the summer and early fall. This explains the differences in average rates of weight gain and feed conversion efficiency. Higher temperatures reduces rate of weight gain due to heat stress but improves feed conversion efficiency by reducing the fraction of feed energy required for maintenance of body temperature.

Rate of Manure Accumulation

The volume of accumulated manure in the Building No. 3 deep pit increased by 13,734 ft³ during the first production cycle and by 15,981 ft³ during the second production cycle. The rates of accumulation for the first and second production cycles were 0.63 ft³ and 0.60 ft³ per 1,000 lb live weight-day, respectively. Both rates are somewhat lower than the rate of 0.80 ± 0.24 ft³ per 1,000 lb live weight-day indicated by Lorimor *et al.* (2000) as typical for grow-finish swine operations with wet-dry feeding systems. However, the rates of manure accumulation observed in this study are within the range of expected values suggested by Lorimore *et al.*

It should be noted that Lorimore *et al.* suggest the higher rate of manure accumulation of 1.07 ± 0.32 ft³ per 1,000 lb live weight per day as being typical for swine operations with dry feeding systems. This value is comparable to the standard reference values of 1.0 and 1.35 ± 0.39 ft³ per 1,000 lb live weight per day proposed, respectively, by the U.S. Department of Agriculture (1992) and the American Society of Agricultural Engineers (2001). This suggests that there is a reasonable degree of consensus regarding the rate of manure accumulation in deep pits for grow-finish swine operations with dry feeding systems. It also indicates that the rate of manure accumulation with wet-dry feeding systems is significantly lower as was observed in this study.

Manure Production

To characterize the transformations and losses that occur as swine manure accumulates in deep pits, it was necessary to determine the quantities of total solids (TS), total volatile solids (TVS), and the other manurial constituents of interest excreted during this study's two feeder pig grow-finish production cycles. As discussed earlier, it was not possible to determine these quantities directly by collecting and analyzing manure excreted by individual animals of groups of animal during this study. Therefore, it was necessary to estimate the quantities of the manurial constituents of interest excreted based on standard reference values suggested as typical excretion rates or nutritional considerations. These standard reference values, listed in Table 4-2, have been published by the USDA (1992) and the ASAE (2001). As shown in this table, the rates suggested as typical by the American Society of Agricultural Engineers (ASAE) are uniformly, and in some instances substantially, higher than the rates suggested as typical by the U.S. Department of Agriculture (USDA).

The selection of the excretion rates used to determine the quantities of TS, TVS, fixed solids (FS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and total sulfur (S) was based on the following evaluation of the validity of the USDA (1992) and the ASAE (2001) suggested excretion rates for TKN and TP. This evaluation was based on comparisons of expected values for rates of excretion of TKN and TP derived from nutritional considerations with the USDA and ASAE rates suggested as typical.

During the two production cycles that occurred during the study, there were 48,451-1,000 lb live weight-days, and 1,460,256 lb of feed with a weighted average crude protein content of 14.5 percent was consumed. These factors translate into the consumption of 211,737 lb of crude protein or 33,878 lb of nitrogen based on the generally accepted assumption that 6.25 lb of crude protein contains one lb of nitrogen. Lewis (1989) indicates that feeder pigs consuming a diet formulated to satisfy but not exceed protein requirements retain 38.7 percent of the nitrogen consumed. Therefore, 12,806 lb of nitrogen should have been retained by the pigs produced during this study and 21,072 lb excreted. This latter value translates into an excretion rate of 0.43 lb of nitrogen per 1,000 lb live weight-day, which is only nominally higher than the excretion

rate suggested as typical (Table 4-2) by the USDA (1992). In contrast, the excretion rate suggested as typical for nitrogen by the ASAE (2001) is approximately 121 percent of this value.

The weighted average phosphorus content of the feed consumed was 1.08 percent, which translates into the consumption of 15,771 lb of phosphorus during the study's two production cycles. For typical feeder pig diets without phytase added to improve the availability phytate phosphorus, Kornegay (1996) suggests that approximately 50 percent of the feed phosphorus is retained and 50 percent is excreted. Based on the amount of feed phosphorus consumed and this assumption, the expected value for phosphorus excreted during this study's two production cycles is 7,786 lb or an excretion rate of 0.16 lb of TP per 1,000 lb live weight-day. This expected rate, again based on nutritional considerations, is exactly the rate suggested as typical (Table 4-2) by the USDA (1992). Conversely, the excretion rate suggested as typical for TP by the ASAE (2001) is approximately 112 percent of this value.

It was not possible to perform similar comparisons for TS, TVS, FS, and COD. However, the results of the comparisons described above suggested that using USDA (1992) excretion rates would produce reasonable estimates of the quantities of these manurial constituents for this study, but using ASAE (2001) values would overestimate these constituents. It was necessary, however, to modify the USDA suggested excretion rate for phosphorus (Table 4-2) to reflect the addition of phytase to the feed used in this study. The USDA suggested typical excretion rates for TP by swine predates the use of phytase in swine feeds. Kornegay (1996) indicates that the addition of this enzyme to swine diets improves phosphorus retention from 50 to 64 percent thereby reducing the rate of phosphorus excretion from 50 to 36 percent of phosphorus consumed. Accounting for phytase reduces the estimated rate of phosphorus excretion for this study from 0.16 lb (Table 4-2) to 0.115 lb per 1,000 lb LW-day.

As indicated in Table 4-2, the USDA (1992) does not suggest a typical swine excretion for sulfur. Although the ASAE (2001) does suggest a typical rate, the coefficient of variation for this rate is greater than 50 percent, indicating significant uncertainty about its validity.

The rate of sulfur excretion by the feeder pigs fed to market weight during this study was therefore estimated as follows. As noted earlier, 1,460,256 lb of feed with a weighted average crude protein content of 14.5 percent was consumed during the study's two production cycles.

The diet fed was a typical corn-soybean diet with a trace mineral and a vitamin premix added along with lysine, dicalcium phosphate, and calcium carbonate. A typical 14.5 percent crude protein corn-soybean meal diet for swine will contain 83.6 percent corn, 13.5 percent soybean meal, and 0.35 percent of a trace mineral premix. These ingredients supply essentially all of the sulfur in the diet. Assuming that the sulfur content (National Research Council, 1982) of ground corn and solvent extracted soybean meal average 0.08 percent and 0.43 percent, respectively, and trace mineral addition in the form of sulfates, the average sulfur content of the feed consumed in this study was calculated to be 3.94 lb per ton.

As noted earlier, 1,460,256 lb (730.1 tons) of feed were consumed during this study's two production cycles. Therefore, an estimated 2,877 lb of sulfur was consumed. Based on the assumption of a pig whole carcass sulfur content of 0.0015 percent (Baker, 1977) and the total weight gain of 521,438 lb during the study's two production cycles (Table 4-1), 782 lb of the sulfur consumed was retained and 2,095 lb was excreted. This translates into an excretion rate of 0.043 lb of sulfur per 1,000 lb live weight-day, which is significantly lower than the ASAE (2001) suggested typical value. However, the rates of addition of copper and zinc as sulfates to swine diets has decreased in recent years due to the problem of copper and zinc accumulating to phytotoxic concentrations in soils where swine manure is applied. It is probable that the ASAE suggested typical rate of sulfur excretion by swine is based on data that predates these reductions.

Because arsenic, copper, and zinc are fed at levels substantially in excess of metabolic requirements (because of their action as growth stimulants), no attempt was made to estimate excretion rates. In addition, it was assumed that the ASAE (2001) suggested rates of excretion of FC and FS are reasonable, given their general agreement with the densities reported by Mara (1974) and in the absence of more definitive information.

In Table 4-3, the estimated quantities of the manurial constituents that were excreted over this study's two production cycles are summarized along with the assumed rates of excretion used for these estimates. As noted, the assumed rates used for the calculation of the quantities of TS, TVS, FS, and COD excreted are the rates suggested as typical by the USDA (1992) while the assumed rates for TKN, TP and S are rates derived from nutritional considerations. Given the

inherent variability in rates of excretion of enteric microorganisms, the ASAE (2001) values are listed only for the purpose of subsequent general comparisons.

Accumulated Manure Characteristics

Table 4-4 summarizes the analyses of the 18 manure samples that were collected from the Building No. 3 deep pit during this study. As the magnitudes of the standard deviations suggest, there was a significant degree of variation among the samples collected. Given the difficulty in obtaining representative samples of the contents of manure storage structures due to settling, the observed degree of variability among individual samples was expected and seems reasonable. With the exception of arsenic, it should be noted that the mean and median concentrations for all parameters are similar, which indicates that the observed values for each parameter are approximately normally distributed. This conclusion was confirmed by results of analyzing the data set for each parameter using the Kolmogorov-Smirnov One-Sample Test (Steel and Torrie, 1980), which indicated that the observed values for each parameter except arsenic were approximately normally distributed ($P < 0.05$). In addition, it was found, using Dixon's Criteria for Testing Extreme Observations in a Single Sample (Snedecor and Cochran, 1980), that suspect values could not be considered outliers ($P < 0.05$).

Therefore, it seems reasonable to conclude that each composite sample collected and analyzed represents a random sample of the manure accumulation in the deep pit. It also should be noted that there were no discernable relationships between concentrations and time for any of the parameters. This observation suggests that the population of the microorganisms responsible for the transformations in the physical and chemical characteristics of the accumulating manure was stable during the period of the study, and it is likely the manure present at the beginning of this study contributed to this stability.

As indicated in Table 4-4, the median concentrations indicate that ammonia nitrogen constituted almost 75 percent of the total nitrogen present, and almost 50 percent of the TP present was in the form of soluble orthophosphate phosphorus as would be expected. However, sulfides constituted only about 30 percent of the S present, which was unexpectedly low given the reducing environment.

Table 4-5 presents the results of the calculations, based on mean and median concentrations and the total volume of manure accumulated to estimate the quantities of the various swine manure constituents that accumulated over the two production cycles that occurred during this study. The differences between the mean and median concentration-based estimates were nominal, with arsenic being the one notable exception.

Material Balances

In Table 4-6, the estimated quantities of the listed manurial constituents excreted and recovered, based on median concentrations (Table 4-5), are compared. As shown, 86.8 percent of the estimated quantity of FS and 91.6 percent of the phosphorus excreted during the study's two production cycles were recovered. Theoretically, 100 percent of the excreted FS and phosphorus should have been recovered given that there is no microbially mediated or abiotic chemical mechanism to cause such losses. It is inherently difficult, however, to obtain truly representative samples from unmixed manure storage structures due to the settling of particulate matter. Specifically, it is essentially impossible to consistently capture the first three to six inches of the accumulated settled solids. Therefore, the recoveries of FS and phosphorus in this study should be considered to be reasonable for sampling deep pits.

The inability to recover the excreted quantities of FS suggests that the recoveries of the other manurial constituents listed in Table 4-6 also are underestimates and the corresponding losses are overestimates. Therefore, it was considered appropriate to conservatively assume that the recoveries listed in Table 4-6 of TVS, COD, TKN, TP, S, FC, and FS also were underestimates and apply a correction factor. In Table 4-7, the results of the materials balances presented Table 4-6 are restated after applying a correction factor of 0.868, which was the percentage recovery of FS (Table 4-6). This approach has been used by Martin and Loehr (1976) and others in evaluations of the performance of animal waste management processes.

As shown in this table, the reduction in organic matter measured as TVS and COD that occurred as manure accumulated in a deep pit during this study's two production was substantial as were the reductions in TKN, S, FC, and FS. The indicated increase in the mass of TP suggests that the estimate of the excretion rate of TP using the previously described methodology was a slight underestimate. Given that the estimate of TP consumed was based on typical values assumed in

the feed formulation process and not analyses of the ingredients used, this margin of error is understandable. The \log_{10} reductions in FC and FC obviously are substantial and indicate that a significant rate of die-off of these indicator organisms occurs during swine manure accumulation and storage in deep pits. It should be recognized, however, that the numbers of these organisms remaining is still very high. For example, the number of FC recovered translates into a density of 6.0×10^6 organisms per 100 ml or 6.2×10^5 organisms per g of TS. As a point of reference, the maximum allowable density of FC in Class A biosolids for disposal on cropland, based on the most probable number, is less than 1,000 organisms, per g of TS (Federal Register, 1993). For Class B biosolids, the maximum allowable density is 2×10^6 organisms per g of TS.

Emissions

Methane—In an anaerobic environment (such as in manure deep pits), loss of organic matter as measured by reductions in TVS and COD can occur only through the reduction of organic carbon to methane or intermediate volatile organic compounds, which desorb from solution. Both the pH and the temperature of the accumulating manure in this study were relatively constant and suggestive of an environment favorable for methanogenic activity. The mean pH was 7.6 ± 0.4 and the temperature remained at a nearly constant 20 °C. Therefore, it seems reasonable to assume that emissions of VOCs were nominal and the reduction in organic matter observed in this study was due to the formation and emission of methane.

Theoretically, the destruction of one lb of ultimate biochemical oxygen demand (BOD_u) under anaerobic conditions should result in the generation of 5.62 ft³ of methane (Metcalf and Eddy, 1991). Although not all COD is biodegradable, it can be assumed that a microbially mediated reduction of COD is equal to a reduction of the same magnitude in BOD_u . On this basis, it is estimated that 719,770 ft³ of methane was emitted during the 289 day period of the study. At a density of 0.04243 lb per ft³, 30,540 lb of methane was emitted. Because methane has approximately 21 times the heat trapping capacity of carbon dioxide (U.S. Environmental Protection Agency, 2002), this is equivalent to the emission of almost 321 tons of carbon dioxide.

On a TVS basis, 6.88 ft³ of methane was emitted per lb of TVS destroyed. Assuming a ratio of methane to carbon dioxide of 60:40, which is typical for manurial biogas, 11.5 ft³ of biogas was produced per lb of TVS destroyed. Biogas production during the anaerobic digestion of

wastewater biosolids typically ranges from 12 to 18 ft³ per lb of TVS destroyed (Metcalf and Eddy, Inc., 1991). Pagilla *et al.* (2000) reported a rate of methane production during the anaerobic digestion of swine manure of nearly 12 ft³ per lb of TVS destroyed.

During this study, 2,373 feeder pigs were finished with a total weight gain of 521,438 lb. Therefore, the estimated methane emission per pig finished and per 1,000 lb of weight gain during this study was 12.9 lb and 58.6 lb, respectively.

In this study, reductions in COD and TVS were 43.6 percent and 40.0 percent, respectively. In comparison, reductions of COD and TVS were 68.8 percent and 64.0 percent, respectively, in an evaluation of the performance of a mixed, mesophilic anaerobic digester on a farrow-to-wean operation (Martin, 2003). This comparison suggests partial anaerobic stabilization of swine manure occurs in deep pits, but deep pit systems do not offer the benefit of using the methane produced as a source of energy.

Hydrogen Sulfide—The loss of 43.6 percent (Table 4-7) or 908 lb of the sulfur excreted during this study translates into the emission of 965 lb of hydrogen sulfide assuming the reduction of excreted sulfur to hydrogen sulfide is essentially complete and emissions of other reduced forms of sulfur are negligible. This translates into an emission factor of approximately 0.41 lb of hydrogen sulfide per pig finished or 1.85 lb per 1,000 lb of weight gain.

Previously, Ni *et al.* (2000) reported emission factors of 6.7 and 7.0 g of hydrogen sulfide per 500 kg live weight-day for two large swine finishing buildings with deep pits based on continuous measurement of the hydrogen sulfide in ventilation system exhaust. These emission factors would translate into hydrogen sulfide emissions of approximately 713 lb and 746 lb (0.30 lb to 0.31 lb of hydrogen sulfide per pig finished) for this study. This comparison suggests that estimating hydrogen sulfide emissions based on ventilation exhaust concentrations may produce underestimates.

Ammonia—The loss of 29.7 percent (Table 4-7) or 6,193 lb of the TKN excreted during this study, translates into the emission of 7,520 lb of ammonia given that ammonia volatilization is the only possible mechanism of significant nitrogen loss from an anaerobic environment. This translates into an emission factor of 3.2 lb of ammonia per pig finished or 14.2 lb per 1,000 lb of

weight gain. Previously, Oosthoek *et al.* (1991) reported a significantly lower ammonia emission factor of 2.2 lb per pig for feeder pigs confined on a slatted floor over a deep pit. This emission factor was based on measured ventilation exhaust ammonia concentrations. Weight gain per pig finished was not reported so an emission factor per 1,000 lb of weight gain could not be reported.

Previously, Martin (2002) reported a loss of 56 percent from a single cell anaerobic lagoon used for swine waste stabilization. Therefore, it appears that deep pits are more effective than anaerobic lagoons in reducing ammonia emissions and conserving swine manure nitrogen. However, ammonia emissions at sites used for land application of manure from deep pits will be higher, unless the manure is immediately incorporated into the soil, given that almost 75 percent of the residual nitrogen is present as ammonia nitrogen.

Water Quality Impacts

The observed reductions in COD and TKN were substantial. Therefore, deep pit systems offer some reduction in the potential impact of this waste on surface waters adjacent to land application sites. However, the potential water quality impact still could be substantial given the remaining readily biodegradable fraction of organic compounds and nutrients present. As discussed earlier, the substantial reductions in FC and FS are not significant given the magnitudes of the numbers of these microorganisms remaining. Thus, it seems reasonable to assume that any concurrent reduction in pathogens present also would not be significant.

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Table 3-1. Study chronology.

Group	Date	Event	Average weight, lb
No. 1	1/7/02	1,142 pigs housed	57
	4/25/02	510 pigs sold	251
	5/16/02	599 pigs sold	283
No. 2	6/10/02	1,275 pigs housed	41
	10/23/02	1,264 pigs sold	270

Table 3-2. Summary of analytical methods.

Parameter	Analytical Method	Reference
Total solids	160.3	USEPA, 1979
Total volatile solids	160.4	USEPA, 1979
Chemical oxygen demand	410.1	USEPA, 1979
Soluble chemical oxygen demand	8000	Hach Company, 1992
Total Kjeldahl nitrogen	955.04	AOAC International, 2002
Ammonia nitrogen	920.03	AOAC International, 2002
Total phosphorus	965.17	AOAC International, 2002
Orthophosphate phosphorus	365.2	USEPA, 1979
Total sulfur	D4239-85	ASTM
Soluble sulfide	8131	Hach Company, 1992
Arsenic	3114B	APHA, 1992
Copper	220.1	USEPA, 1979
Zinc	968.08	Hach Company, 1992
Fecal coliforms	9222D	APHA, 1992
Fecal streptococcus	9230C	APHA, 1992
pH	150.1	USEPA, 1979

Table 4-1. Summary of animal performance.

Group	Total weight gain, lb	Average rate of weight gain, lb/day	Feed conversion efficiency, lb of feed/ lb weight gain	Mortality, %
No. 1	297,527	1.79*	2.98	2.9
No. 2	289,005	1.70	2.65	0.9

* Average rate of gain was 1.81 lb per day for the 510 pigs sold on 4/25/02 and 1.77 lb per day for the 599 pigs sold on 5/16/02.

Table 4-2. Comparison of suggested typical rates of excretion of various swine manure constituents, lb per 1,000 lb live weight-day.

Parameter	U.S. Department of Agriculture (1992)	American Society of Agricultural Engineers (2001)
Total solids	6.34	11 ± 6.3
Total volatile solids	5.40	8.5 ± 0.66
Fixed solids	0.94	
Chemical oxygen demand	6.06	8.4 ± 5.3
Total Kjeldahl nitrogen	0.42	0.52 ± 0.21
Total phosphorus	0.16	0.18 ± 0.10
Total sulfur	—	0.076 ± 0.040
Copper	—	0.0012 ± 0.0084
Zinc	—	0.0050 ± 0.0025
Fecal coliforms*	—	10.9 ± 10.7
Fecal streptococcus*	—	12.4 ± 12.1

*Transformed to log₁₀ colony forming units.

Table 4-3. Estimated quantities of the listed manurial constituents excreted during this study's two production cycles.

Parameter	Excretion rate, lb per 1,000 lb live weight-day	Total excreted, lb
Total solids	6.34 [*]	307,179
Total volatile solids	5.40 [*]	261,635
Fixed solids	0.94 [*]	45,544
Chemical oxygen demand	6.06 [*]	293,613
Total Kjeldahl nitrogen	0.43 [†]	20,834
Total phosphorus	0.115 [†]	5,572
Total sulfur	0.043 [†]	2,083
Fecal coliforms	10.9±12.7 ^{#§}	15.6±15.5 [#]
Fecal streptococcus	12.4±12.1 ^{#§}	17.1±16.7 [#]

^{*}USDA (1992)

[†]Estimated from nutritional considerations

[#]ASAE (2001)

[§]Log₁₀ colony forming units

Table 4-4. Physical and chemical characteristics of the manure accumulation in the Building
No. 3 deep pit from January 11 through October 23, 2002.

Parameter	Mean \pm standard deviation *	Median
Total solids, mg/L	91,778 \pm 21,053	94,950
Total volatile solids, mg/L	71,064 \pm 18,173	73,485
Fixed solids, mg/L	20,714 \pm 3,085	21,307
Chemical oxygen demand, mg/L	81,524 \pm 25,851	77,450
Soluble chemical oxygen demand, mg/L	20,117 \pm 8,002	19,100
Total Kjeldahl nitrogen, mg/L	6,944 \pm 338	6,850
Organic nitrogen, mg/L	1,906 \pm 437	2,000
Ammonia nitrogen, mg/L	5,039 \pm 449	5,100
Total phosphorus, mg/L	2,546 \pm 556	2,751
Orthophosphate phosphorus, mg/L	1,399 \pm 282	1,350
Total sulfur, mg/L	556 \pm 255	550
Soluble sulfide, mg/L	202 \pm 108	163
Arsenic, mg/kg [†]	0.14 \pm 0.21	0.06
Copper, mg/kg	100 \pm 17	102

Table 4-4. Continued.

Zinc, mg/kg	92±20	96
pH	7.8±0.4	7.6
Fecal coliforms, log ₁₀ CFU/100 ml [#]	4.94±1.72	4.97
Fecal streptococcus, log ₁₀ CFU/100 ml	5.59±0.56	5.73

* n=18

† mg per kg wet weight.

log₁₀ colony forming units per 100 ml.

Table 4-5. Estimated accumulations of the parameters listed over the study's two production cycles.

Parameter	Residual mass based on mean concentrations	Residual mass based on median concentrations
Total solids	170,271 lb	176,156 lb
Total volatile solids	131,842 lb	136,133 lb
Fixed solids	38,429 lb	39,530 lb
Chemical oxygen demand	151,248 lb	143,689 lb
Soluble chemical oxygen demand	37,433 lb	35,435 lb
Total Kjeldahl nitrogen	12,833 lb	12,708 lb
Total phosphorus	4,723 lb	5,104 lb
Soluble orthophosphate phosphorus	2,595 lb	2,505 lb
Total sulfur	1,050 lb	1,020 lb
Soluble sulfide	375	302 lb
Arsenic	0.98 lb	0.43 lb
Copper	702 lb	716 lb
Zinc	646 lb	673 lb

Table 4-5. Continued.

Fecal coliforms	11.87 log ₁₀ CFU*	11.90 log ₁₀ CFU
Fecal streptococci	12.88 log ₁₀ CFU	12.66 log ₁₀ CFU

* Colony forming units.

Table 4-6. Results of materials balances.

Parameter	Excreted, lb	Recovered, lb[*]	Residual, percent of excreted
Total solids	307,179	176,156	57.3
Total volatile solids	261,635	136,133	52.1
Fixed solids	45,544	39,530	86.8
Chemical oxygen demand	293,613	143,689	48.9
Total Kjeldahl nitrogen	20,834	12,708	61.0
Total phosphorus	5,572	5,104	91.6
Total sulfur	2,083	1,020	49.0
Fecal coliforms, log ₁₀ CFU [†]	15.6±15.5	11.9	99.98
Fecal streptococcus, log ₁₀ CFU	17.7±16.7	12.7	99.99

^{*}Based on median concentrations.

[†]Log₁₀ colony forming units.

Table 4-7. Results of adjusted materials balances.

Parameter	Excreted, lb	Recovered after adjustment, lb	Loss, %
Total volatile solids	261,635	157,066	40.0
Chemical oxygen demand	293,613	165,540	43.6
Total Kjeldahl nitrogen	20,834	14,641	29.7
Total phosphorus	5,572	5,880	+5.5
Total sulfur	2,083	1,175	43.6
Fecal coliforms, log ₁₀ CFU*	15.6±15.5	13.7	98.7
Fecal streptococcus, log ₁₀ CFU	17.1±16.7	14.6	99.7

*Log₁₀ colony forming units.