Emissions of Ammonia, Hydrogen Sulfide, and Odor Before, During and After Slurry Removal from a Deep-Pit Swine Finisher

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ABSTRACT

It is a fairly common practice in the Midwestern U.S. to raise swine in buildings with under-floor slurry storage systems designed to store manure for one year. These so called "deep-pit" systems can represent a concentrated source for the emissions of ammonia (NH_3), hydrogen sulfide (H_2S), and odors.

As part of a larger six-state research effort (USDA-IFAFS Project, "Aerial Pollutant Emissions from Confined Animal Buildings"), real-time NH_3 and H_2S with incremental odor emission data was collected over two annual slurry removal events. For this study, two 1000-head deep-pit swine finishing facilities in central Iowa were monitored with one-year storage of slurry maintained in a 2.4 m tall holding tank below the animal

occupied zone. Results show that the H_2S emission, measured with four independent slurry removal events over two years, increased by an average of 62 times relative to the before-removal emission levels. This increase was shown to persist during the agitation process of the slurry which on average occurred over an 8 hr time period. At the conclusion of slurry agitation, the H_2S emission decreased by an average of 10 times the before-removal emission level. NH_3 emission during agitation increased by an average of 4.6 times the before-removal emission level and increased by an average of 1.5 times the before-removal emission level after slurry removal was completed. Odor emission increased by a factor of 3.4 times the before-removal odor emission level and decreased after the slurry-removal event by a factor of 5.6 times the before-removal emission level. The results indicate that maintaining an adequate barn ventilation rate regardless of animal comfort demand is essential to keeping gas levels inside the barn below hazardous levels.

IMPLICATIONS

Deep-pit slurry removal events lead to elevated H_2S, odor, and NH_3 concentrations and emissions. The gas of most concern is H_2S as this gas can reach levels dangerous to animals and workers. These results highlight the need for a pre-planned protocol that must be established for barn ventilation rate maintenance to ensure that H_2S concentrations do not reach lethal levels.

INTRODUCTION

Many swine finished (reared from 15 or 40 lbs to 260 lbs) in the Midwestern U.S. are raised in structures where year-long storage of manure is present below the occupied zone of the animals. These so-called deep-pit systems represent a concentrated source of nutrients that once applied judiciously to the soil provide an excellent source of fertilizer. The standard method for manure removal from buildings using deep-pit manure storage is to provide significant mixing of the slurry before and during slurry removal to suspend solids and to provide a consistent manure product. This process commonly takes place in the fall after crops have been removed or in early spring before planting begins and generally takes from one to 3 days 1000-pigs depending upon off-site hauling capacities.

This process of slurry removal can represent an acute concentrated emission source for gases and odors. Removal of slurry involves the in situ mixing and agitation of the manure and subsequent application to the field. Significant problems can arise during this phase of swine production if attention to detail is not maintained. Turbulent activity of the slurry surface can result in very rapid release of odors, NH_3, and H_2S, the latter of which has been linked to several animal and human casualties. Nuisance complaints related to swine production are generally highest during slurry removal and subsequent land application. The objective of this paper is to report on the emission of NH_3, H_2S, and odors before, during, and after slurry removal from a two identical deep-pit swine finishing facilities located in the Midwestern part of the U.S over two annual slurry removal events.

Swine Housing Ammonia Emissions

Several U.S. and northern European studies have investigated the emission of gases from livestock and poultry production systems. Typically, the gases investigated include NH_3, H_2S, and the general class of VOCs associated with livestock odors[1]. Recently, the need to study the concentrations of these gases in the community surrounding livestock and poultry operations has surfaced due to increasing pressure from regulatory agencies. The following literature review focuses on the emissions from swine housing. A more complete review of the literature on emissions can be found in Hoff et al.[2]

Aarnink et al.[3] studied the NH_3 emission patterns of nursery and finishing pigs raised on partially slatted flooring. They found that for nursery pigs, an average increase of 16 mg NH_3 pig^{-1} day^{-1} was measured and this increased to 85 mg NH_3 pig^{-1} day^{-1} (4.8 mg NH_3 m^{-2} hr^{-1}) for finishing pigs. The overall average NH_3 emission measured was between 0.70 and 1.20 g NH_3 pig^{-1} day^{-1} for nursery pigs (19-33 g NH_3 AU^{-1} day^{-1}; 1 AU = animal unit = 500 kg) and between 5.7 and 5.9 g NH_3 pig^{-1} day^{-1} (331 mg NH_3 m^{-2} hr^{-1}) for finishing pigs (42-43 g NH_3 AU^{-1} day^{-1}). They found an increase in NH_3 emission during the summer months for nursery pigs due to higher ventilation rates but this same trend was not found for finishing pigs. They also found that removing the under-floor stored slurry reduced the NH_3 emission by about 20% for a period of 10 hours, after which time the NH_3 emission regained the pre-removal emission level.

Demmers et al.[4] investigated the exhausted concentrations and emission rates of NH_3 from mechanically ventilated swine buildings. They reported NH_3 concentrations in a swine finishing house between 12 and 30 mg NH_3 m^{-3} with an average NH_3 emission rate of 46.9 kg NH_3 AU^{-1} $year^{-1}$ (160 g NH_3 AU^{-1} day^{-1} or 1,008 mg NH_3 m^{-2} hr^{-1}).

Burton and Beauchamp[5] studied the relationship between outside temperature, ventilation system response, in-house NH_3 concentration, and the resulting emission of NH_3 from the swine housing unit. They clearly showed the inverse relationship of in-house NH_3 concentration with outside temperature and the direct relationship of NH_3 emission from the swine housing unit with outside temperature. This trend was attributed to the increased ventilation rates required during the summer to control inside climate temperatures for the housed animals. They summarized results over a one-year period and reported the monthly averages. February had the highest in-house concentration at 15 mg NH_3-N L^{-1} corresponding to the lowest emission rate at 0.9 kg NH_3-N day^{-1}. August had the lowest in-house concentration of 4 mg NH_3-N L^{-1} and, correspondingly, the highest emission rate of 3.2 kg NH_3-N day^{-1}, on average.

Ni et al.[6] investigated the exhausted concentrations and emission rates of NH_3 in and from a deep-pit swine finishing building with and without the presence of animals and with pits that were roughly half full (1.3 m manure depth; 2.4 m depth capacity). They investigated the gas release rates with and without the effect of heating the building through unit space heaters. Without the presence of animals, they measured NH_3 concentrations between 6 and 15 parts-per-million (ppm) with emission rates between 40 and 58 mg NH_3 m^{-2} hr^{-1} (5-8 g NH_3 AU^{-1} day^{-1}). When the buildings were re-stocked with pigs, exhaust air concentrations of NH_3 were on average 15.2 ppm with corresponding emission rates of 233 mg NH_3 m^{-2} hr^{-1} (40-50 g NH_3 AU^{-1} day^{-1}).

Groot Koerkamp et al.[7] conducted an extensive study of NH_3 emissions from swine housing facilities. They investigated both indoor NH_3 levels and with simultaneous measurements of building ventilation rates and reported the resulting emission rates. In general, NH_3 concentrations varied between 5 and 18 ppm, with average emission rates between 649 and 3,751 mg NH_3 AU^{-1} hr^{-1} (16-90 g NH_3 AU^{-1} day^{-1} or between 122-706 mg NH_3 m^{-2} hr^{-1}).

Hinz and Linke[8] investigated the indoor concentrations and emissions of NH_3 from a mechanically ventilated swine finishing facility during a grow-out period where pigs ranged between 25 and 100 kg. Interior NH_3 concentrations during the grow-out varied from 10 to 35 ppm and these were inversely proportional to outside temperature. Emission rate of NH_3 varied from 70 g NH_3 hr^{-1} (38 kg average pig weight) to 210 g NH_3 hr^{-1} (83 kg average pig weight) resulting in an average NH_3 emission rate of 66 g NH_3 AU^{-1} day^{-1} (518 mg NH_3 m^{-2} hr^{-1}).

Zahn et al.[9] studied the NH_3 emission rate from both deep-pit and pull-plug swine finishing facilities during summer periods. They found that the NH_3 emission rates were very similar for these two facility types and grouped the emission data into an overall average of 66 ng NH_3 cm^{-2} s^{-1} (311 g NH_3 AU^{-1} day^{-1} or 2,376 mg NH_3 m^{-2} hr^{-1}).

Zhu et al.[10] studied the daily variations in NH_3 emissions from various mechanically and naturally ventilated swine housing systems. For a mechanically ventilated swine gestation facility, they measured internal NH_3 concentrations between 9 and 15 ppm, with emission rates consistent at about 5 μg NH_3 m^{-2} s^{-1} (2.2 g NH_3 AU^{-1} day^{-1}). For a mechanically ventilated farrowing facility, they measured internal NH_3 concentrations between 3 and 5 ppm, with emission rates ranging between 20 and 55 μg NH_3 m^{-2} s^{-1} (15-42 g NH_3 AU^{-1} day^{-1}). For a mechanically ventilated nursery facility, they measured internal NH_3 concentrations between 2 and 5 ppm, with emission rates ranging between 20 and 140 μg NH_3 m^{-2} s^{-1} (23-160 g NH_3 AU^{-2} day^{-1}). For a mechanically ventilated finishing facility, they measured internal NH_3 concentrations between 4 and 8 ppm, with emission rates ranging between 20 and 55 μg NH_3 m^{-2} s^{-1} (10-26 g NH_3 AU^{-2} day^{-1} or between 72-198 mg NH_3 m^{-2} hr^{-1}). For a naturally ventilated finishing facility with pit exhaust fans, they measured internal NH_3 concentrations between 7 and 15 ppm, with emission rates ranging between 60 and 170 μg NH_3 m^{-2} s^{-1} (28-80 g NH_3 AU^{-2} day^{-1} or between 216-612 mg NH_3 m^{-2} hr^{-1}).

Osada et al.[11] investigated the NH_3 emission from a swine finisher over an 8 wk period comparing under-floor stored manure (control) and under-floor manure removed weekly (treatment). They reported only slight differences in NH_3 emission rates with the control at 11.8 kg NH_3 AU^{-1} yr^{-1} (32 g NH_3 AU^{-1} day^{-1} or 255 mg NH_3 m^{-2} hr^{-1}) and the treatment at 11.0 kg NH_3 AU^{-1} yr^{-1} (30 g NH_3 AU^{-1} day^{-1}).

Swine Housing Hydrogen Sulfide Emissions

Ni et al.[6] investigated the exhausted concentrations and emission rates of H_2S in a deep-pit swine finishing building with and without the presence of animals and with pits that were roughly half full (1.3 m depth, 2.4 m depth capacity). They investigated the gas release rates with and without the effect of heating the building through unit space heaters. They measured H_2S concentrations ranging from 221 to 1,492 parts-per-billion (ppb) with corresponding emission rates between 1.6 and 3.8 mg H_2S m^{-2} hr^{-1} (0.22-0.49 g H_2S AU^{-1} day^{-1}). When the buildings were re-stocked with pigs, exhaust air concentration of H_2S averaged 423 ppb with a corresponding emission rate of 9.4 mg H_2S m^{-2} hr^{-1} (1.25 g H_2S AU^{-1} day^{-1}).

Zahn et al.[9] studied the H_2S emission rate from both deep-pit and pull-plug swine finishing facilities during summer periods. They found that the H_2S emission rates were very similar for these two facility types and grouped the emission data into an overall average of 0.37 ng H_2S cm^{-2} s^{-1} (1.7 g H_2S AU^{-1} day^{-1} or 13.3 mg H_2S m^{-2} hr^{-1}).

Zhu et al.[10] studied the daily variations in H_2S emissions from various mechanically and naturally ventilated swine housing systems. For a mechanically ventilated swine gestation facility, they measured internal H_2S concentrations between 500 and 1200 ppb, with emission rates consistent at about 2 μg H_2S m^{-2} s^{-1} (1 g H_2S AU^{-1} day^{-1}). For a mechanically ventilated farrowing facility, they measured internal H_2S concentrations between 200 and 500 ppb, with emission rates consistent at about 5 μg H_2S m^{-2} s^{-1} (4 g H_2S AU^{-1} day^{-1}). For a mechanically ventilated nursery facility, they measured internal H_2S concentrations between 700 and 3400 ppb, with emission rates ranging between 20 and 140 μg H_2S m^{-2} s^{-1} (23-160 g H_2S AU^{-1} day^{-1}). For a mechanically ventilated finishing facility, they measured internal H_2S concentrations between 300 and 600 ppb, with emission rates consistent at about 10 μg H_2S m^{-2} s^{-1} (5 g H_2S AU^{-1} day^{-1} or 36 mg H_2S m^{-2} hr^{-1}). For a naturally ventilated finishing facility with pit exhaust fans, they measured internal H_2S concentrations between 200 and 400 ppb, with emission rates ranging between 5 and 15 μg H_2S m^{-2} s^{-1} (2 and 7 g H_2S AU^{-1} day^{-1} or between 18 and 54 mg H_2S m^{-2} hr^{-1}).

Summary

A large variation in both NH_3 and H_2S emission rates from swine house ventilation air have been reported. Considering the literature cited, the range of H_2S emissions expected for finishing pigs are between 9.4 and 54 mg H_2S m^{-2} hr^{-1} from the ventilation air for swine finishing pigs. The range of NH_3 emissions expected are between 72 and 2376 mg NH_3 m^{-2} hr^{-1} from the ventilation air for swine finishing pigs, with the dominating average emission rates in the 300 and 500 mg NH_3 m^{-2} hr^{-1} range. The study by Hinz and Linke[8] also pointed out the changes in emission rates expected as finishing pigs mature, with a reported threefold increase between 38 and 83 kg average body weight.

FACILITY DESCRIPTION

Two identical deep-pit swine finishing facilities in central Iowa were monitored for this research project and this arrangement represents one of six U.S. sites monitored for a larger six-state emissions study funded by the U.S. Department of Agriculture under the USDA- Initiative for Future Agricultural Systems (IFAFS) program. Each facility monitored, as shown in Figure 1, was designed to house 1000-pigs ranging in weight between about 20 and 120 kg. Slurry was stored in a 2.4 m deep holding concrete basin below a fully-slatted concrete floor and was designed to store this manure for one calendar year. Slurry removal was conducted once per yr and this was done in the fall (October), never in the spring.

Each barn was fan-ventilated for all seasons using a combination of methods. The cold-to-mild weather ventilation was handled with a series of pit (Fans 1,2) , side (Fan 3), and end-wall (or tunnel) fans (Fans 4,5; see Figure 1) in combination with a series of 10 rectangular center-ceiling inlets (not shown) to distribute fresh air within the building. The warm-to-hot weather ventilation was handled with tunnel ventilation where all fans except Fan 3 were used in combination with an adjustable curtain at the opposing end wall. During this tunnel mode of ventilation, the 10 center-ceiling inlets inside the barn were closed. The barn was controlled for temperature with the inlet distribution system controlled via static pressure. As barn temperature demanded airflow rate changes, the inlet distribution system would adjust accordingly to maintain a desired operating static pressure of 20 Pa.

The layout given in Figure 1 includes a Mobile Emission Laboratory (MEL) that housed all instrumentation required to measure gas concentrations, pertinent environmental data, and the monitoring of barn ventilation rate. Ammonia (Model 17C chemiluminescence; TEI, Inc), H_2S (Model 45C pulsed fluorescence; TEI, Inc), and CO_2 (Model 3600 infrared, MSA, Inc) were measured at 12 locations, 6 from Barn 1 and 6 from Barn 2. A solenoid switching system allowed gas samples to be delivered to each analyzer simultaneously in 10-min switching increments. Therefore, each location was measured for 10 min every 2 hrs. Environmental variables such as temperature, relative humidity, static pressure, and endwall curtain opening level were measured as well. Ventilation rate was measured by recording the on/off status of all single-speed fans (Fans 5,6,7,8; Figure 1) and the on/off status along with fan rpm levels for all variable speed fans (Fans 1,2,3,4). Individual fan airflow rates were measured in situ using a FANS unit described in Casey et al.[12] Specific details related to the MEL set-up and quality assurance/quality control procedures can be found in Heber et al.[13] and Jacobson et al.[14]

For emission calculations, the exhausted airflow rate along with the corresponding gas concentration at each emission point was measured. For the barns shown in Figure 1, three emission locations were monitored: the blended pit ventilation air from Fans 1 and 2, the emission at the sidewall Fan 3, and the emission from the combination of Fans 4 to 8 (tunnel end). Emission rates were calculated as

$$E = \sum (Q_o C_o - Q_i C_i) = \sum (Q_o^{'} C_o^{'} - Q_i^{'} C_i^{'}) \qquad (1)$$

where

C_i Mass concentration at the barn air inlet, mg/m^3 or µg/m^3

E, Barn emission rate, mg/s or µg/s

C_o Mass concentration at the barn air exhaust, mg/m^3 or µg/m^3

C_i’ Standardized mass concentration at the barn air inlet (based on STP), mg/sm^3 or µg/sm^3

C_o’ Standardized mass concentration at the barn exhaust (based on STP), mg/sm^3 or µg/sm^3

Q_o Barn outlet moist airflow rate at T_o, m^3/s

Q_i Barn inlet moist airflow rate at T_i, m^3/s

Q_i’ Moist standard ventilation rate at the barn inlet (based on STP), sm^3/s

Q_o’ Moist standard ventilation rate at barn exhaust (based on STP), sm^3/s

The standard conditions, STP, used were a temperature of 20 °C and a pressure of 101,325 Pa.

Slurry was removed from each building in October after the harvest. Table 1 outlines the scheduled slurry removal events for the years 2002 and 2003. The results given in this paper involve the emissions measured for roughly 6 days surrounding these slurry removal events. The procedure followed a strict protocol before starting each slurry removal event. Before the slurry was agitated, the producer would manually override the ventilation control system by establishing an airflow rate close to 37 fresh-air changes per hr, opened all 10 center-ceiling inlet diffusers, and made sure that the end-wall curtain used for tunnel ventilation was closed. After these adjustments were made, usually more than 1 hour before agitation, the barn was deemed ready for agitation and slurry removal. The ventilation system was then left alone in manual mode throughout the entire slurry removal event and no one was allowed in the barn during the slurry-removal event. Each slurry removal event for a barn took from 7 to 8.5 hrs as shown in Table 1.

RESULTS AND DISCUSSION

The results presented summarize the NH_3, H_2S, and odor emissions before, during, and after slurry was removed from Barns 1 and 2. The results are intended to characterize the emission changes that occur during and after slurry removal and the potential concentrations reached in the barn during slurry removal.

Table 2 shows the average H_2S concentration (ppb) before the slurry was agitated, the maximum H_2S concentration during slurry removal, and the average concentration after the slurry was removed from each barn for the two years reported. Table 2 summarizes the concentrations associated with each of the three possible emission points (pit, sidewall, and tunnel fans). The averages recorded in Table 2 were for the 6 hrs either before or after slurry was removed from the barn.

The overall maximum H_2S concentration reached 35,825 ppb for Barn 2, at the pit exhaust fan for Barn 2 during the 2003 removal event. On average, the hydrogen sulfide concentration measured at the pit fan exhaust location reached a level that was 18 times higher during agitation as compared to the before-removal level. For the sidewall and tunnel fan exhaust locations, the average H_2S concentration was 27.7 times higher during slurry-removal compared to the before-removal concentration.

The characteristics of an emission event experienced during slurry removal are shown in Figure 2. Figure 2a shows the barn temperature, outside temperature, and total barn airflow rate and Figure 2b shows the total barn H_2S emission rate (mg H_2S m^{-2} hr^{-1}) and the associated total barn airflow rate (m^3 hr^{-1}) for Barn 1 during the 2003 removal event. As shown in Table 1, this barn was emptied over a two-day period and the multiple elevated emission events are clearly evident. The ambient temperature ranged from a high/low of 23 °C and 8 °C for 21 October 2003 and a high/low of 24 °C and 3 °C for 22 October 2003, respectively. The owner of this operation routinely bypassed the barn's automatic control system during a slurry removal event to ensure an adequate ventilation rate for the barn by manually turning selected tunnel fans on. The elevated ventilation rate initiated by the owner surrounding both slurry removal events is clearly evident in Figure 2. The elevated H_2S emission rate is clearly evident and dramatic. The emission shown was in direct correlation with slurry agitation, resulting in an elevated H_2S emission rate within three minutes after the slurry was agitated, and fell as quickly once slurry agitation stopped. Figure 3 shows the characteristic H_2S emission for a slurry removal event that occurred over one continuous agitation and removal period. The manual override on the ventilation system resulted in a barn ventilation rate that increased from 13,200 m^3 hr^{-1} to an average of 56,000 m^3 hr^{-1}. In other words, the barn, running in automatic control, would have ventilated the space at about 13,200 m^3-hr^{-1} or 6.5 fresh-air changes per hr. With the operator's manual override of the ventilation system, the barn was allowed to ventilate at 56,000 m^3 hr^{-1} or 27 fresh-air changes per hour. This characteristic points out the need for the establishment of a ventilation protocol before ever considering the agitation of slurry, regardless of the depth of slurry in the holding pit.

The H_2S and NH_3 emissions for the four slurry removal events are summarized in Table 3. The "before" and "after" averages were determined by the 24-hr period before the barn was agitated and the 24-hr period after the slurry was removed from the barn. As shown in Table 3, a very large variation in H_2S emission rates existed before, during, and after slurry removal. The absolute maximum H_2S emission rate measured for the four events was 1,553 mg H_2S m^{-2} hr^{-1}. The average H_2S emission rate for the four slurry removal events was 1,364±179 mg H_2S m^{-2} hr^{-1}. The average before and after H_2S emission rate for the four slurry removal events was 31.3±23.2 mg H_2S m^{-2} hr^{-1} and 3.4±1.7 mg H_2S m^{-2} hr^{-1}, respectively. The average NH_3 emission rate for the four slurry removal events was 1,639±632 mg NH_3 m^{-2} hr^{-1}. The average before and after NH_3 emission rate for the four slurry removal events was 394±224 mg NH_3 m^{-2} hr^{-1} and 570±329 mg NH_3 m^{-2} hr^{-1}, respectively. Consistently, the after slurry removal NH_3

emission rate was higher than the before-removal level. A typical NH_3 emission event is shown in Figure 4 for the slurry removal event shown in Figure 3.

Odor data was collected for this research project at two-week intervals. However, during the slurry removal event for Barn 2 in 2003, a more detailed odor evaluation procedure was conducted to try and capture the odor emitted during slurry agitation and manure removal. Table 4 and Figure 5 summarize the measured results. The increase in odor strength (OU-m^{-3}) during slurry removal was 4.3 and 2.1 times higher for the pit and tunnel fan exhaust locations, respectively, compared to the before-removal levels. The after-removal odor strength was 1.3 and 3.0 times lower than the before-removal levels. The maximum odor strength during slurry removal reached 9625 OU-m^{-3} and 8228 OU-m^{-3} for the pit and tunnel exhaust locations, respectively. During slurry agitation, the odor emission rate (OU m^{-2} s^{-1}) had a maximum level of 19.8 and 116.6 OU m^{-2} s^{-1} for the pit and tunnel exhaust fan locations, respectively. The odor strength measurements indicated that the pit and tunnel exhaust points were relatively similar before, during, and after slurry removal. However, the odor emission is nearly 6 times higher from the tunnel exhaust point due to the much higher airflow rate from this exhaust location relative to the pit exhaust location.

CONCLUSIONS

The emission of H_2S, NH_3, and odor before, during, and after slurry removal events from two deep-pit swine finishing facilities indicated large increases in concentrations and emission rates during slurry removal with odor and H_2S emissions lowering to levels well below the pre-removal rates. Although at times the pit exhaust concentrations can be much higher than from non-pit fans, the emission of H_2S, NH_3, and odor from the pit fans is substantially lower than the predominant tunnel fans due to the large differences in ventilation rate capacities when tunnel fans are active. A slurry removal event will result in an acute exposure event for the animals and workers. A protocol establishing a minimum ventilation rate at and above 30 fresh-air changes per hr should be established before agitation begins and all workers should remain outside the facility during agitation.

REFERENCES

1. O'Neill, D.H.; Phillips, V.R. A review of the control of odor nuisance from livestock buildings: Properties of the odorous substances which have been identified in livestock wastes in the air around them. *J. Agric. Eng. Res*. **1992,** *53*, 23-50.

2. Hoff, S.J.; Hornbuckle, K.C.; Thorne, P.S.; Bundy, D.S.; O'Shaughnessy, P.T. Chapter 4. Emissions and Community Exposures from CAFOs. Iowa Concentrated Animal Feeding Operations Air Quality Study. Iowa State University and the University of Iowa. http://www.public-health.uiowa.edu/ehsrc/CAFOstudy.htm (accessed September 2004).

3. Aarnink, A.J.A.; Keen, A.; Metz, J.H.M.; Speelman, L.; Verstegen, M.W.A. Ammonia emission patterns during the growing periods of pigs housed on partially slatted floors. *J. Agric. Eng. Res*. **1995,** *62*, 105-116.

4. Demmers, T.G.M.; Burgess, L.R.; Short, J.L.; Phillips, V.R.; Clark, J.A.; Wathes, C.M. Ammonia emissions from two mechanically ventilated UK livestock buildings. *Atmos. Environ.* **1999,** *33*, 217-227.

5. Burton, D.L.; Beauchamp, E.G. Nitrogen losses from swine housings. *Agric. Wastes* **1986,** *15*, 59-74.

6. Ni, J.Q.; Heber, A.J.; Diehl, C.A.; Lim, T.L. Ammonia, hygrogen sulphide and crbon dioxide release from pig manure in under-floor deep pits. *J. Agric. Eng. Res*. **2000,** *77* (1),53-66.

7. Groot Koerkamp, P.W.G.; Metz, J.H.M.; Uenk, G.H.; Phillips, V.R.; Holden, M.R.; Sneath, R.W.; Short, J.L.; White, R.P.; Hartung, J.; Seedorf, J.; Schroeder, M.; Linkert, K.H.; Pedersen, S.; Takai, H.; Johnsen, J.O.; Wathes, C.M. Concentrations and emissions of ammonia in livestock buildings in northern Europe. *J. Agric. Eng. Res.* **1998,** *70*, 79-95.

8. Hinz, T; Linke, S. A comprehensive experimental study of aerial pollutants in and emissions from livestock buildings. Part 2: Results. *J Agric. Eng Res*. **1998,** *70*, 119-129.

9. Zahn, J.A.; Hatfield, J.L.; Laird, D.A.; Hart, T.T.; Do, Y.S.; Dispirito, A.A. Functional classification of swine manure management systems based on effluent and gas emission characteristics. *J. Environ. Qual*. **2001,** *30*, 635-647.

10. Zhu, J.; Jacobson, L.; Schmidt, D.; Nicolai, R. Daily variations in odor and gas emissions from animal facilities. *Appl. Eng. in Agric.* **2000,** *16* (2), 153-158.

11. Osada, T.; Rom, H.B.; Dahl, P. Continuous measurement of nitrous oxide and methane emission in pig units by infrared photoacoustic detection. *Trans. ASAE* **1998,** *41* (4), 1109-1114.

12. Casey, K.D.; Gates, R.S.; Wheeler, E.F.; Zajaczkowski, J.S.; Topper, P.A.; Xin, H.; Liang, Y. Ammonia emissions from broiler houses in Kentucky during winter. International Symposium on Control of Gaseous and Odour Emissions from Animal Production Facilities, Horsens, Denmark, June 1-4, 2003. pp. 213-220.

13. Heber, A.J.; Ni, J.Q.; Lim, T.T.; Tao, P.C.; Millmier, A.M.; Jacobson, L.D.; Nicolai, R.E.; Koziel, J.A.; Hoff, S.J.; Zhang, Y.; Beasley, D.B. 2002. Quality assured measurements of animal building emissions: Part 1. Gas concentrations. Symposium on Air Quality Measurement Methods and Technology, San Francisco, CA, November 13-25, 2002; A&WMA: Pittsburgh, PA, 2002.

14. Jacobson, L.D.; Heber, A.J.; Zhang, Y.; Sweeten, J.; Koziel, J.; Hoff, S.J.; Bundy, D.S.; Beasley, D.B.; Baughman, G.R. 2003. Air pollutant emissions from confined animal buildings in the U.S. In *Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities,* Horsens, Denmark, June 1-4, 2003.

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Table 1. Slurry removal scheduling.

Year	Barn	Date Started	Date Ended	Time Start	Time End
2002	1	October 16	October 16	11:45	18:00
	2	October 18	October 18	10:00	17:00
2003	1*	October 21	October 21	18:00	22:00
		October 22	October 22	09:30	14:00
	2	October 20	October 20	10:00	18:30

* Barn 1 in 2003 emptied in 2 separate events over a two-day period.

Year	Barn	Date Started	Date Ended	Time Start	Time End
2002	1	October 16	October 16	11:45	18:00
	2	October 18	October 18	10:00	17:00
2003	1*	October 21	October 21	18:00	22:00
		October 22	October 22	09:30	14:00
	2	October 20	October 20	10:00	18:30

Table 2. Hydrogen sulfide concentration (ppb) before, during, and after slurry removal.

Year	Barn	Before	Max During	After	Date	Location
2002	1	272	9,990*	79	10/16/02	pit
		592	9,833	197	10/16/02	sidewall
		473	9,990*	186	10/16/02	tunnel
	2	1,084	5,455	31	10/18/02	pit
		1,775	11,990	43	10/18/02	sidewall
		857	15,918	30	10/18/02	tunnel
2003	1**	397	850	467	10/21/03	pit
		467	22,245	69	10/22/03	pit
		336	3,128	678	10/21/03	sidewall
		678	12,011	71	10/22/03	sidewall
		337	11,957	148	10/21/03	tunnel
		148	16,378	71	10/22/03	tunnel
	2	2,067	35,825	93	10/20/03	pit
		460	7,840	55	10/20/03	sidewall
		1,360	8,075	69	10/20/03	tunnel

* Exceeded maximum set range of analyzer which was 10,000 ppb. Analyzer subsequently changed to a range of 50,000 ppb.

** Barn slurry emptied over two days; “after” on 10/21/03 the same as “before” on 10/22/03.

Table 3. Measured emission levels for H_2S and NH_3 in mg m^{-2} hr^{-1}. Both barns had a floor area of 837 m^2. Barn 1 had 58,900 kg of pigs and barn 2 had 52,500 kg for year 2002 during pump-out. Barn 1 had 103,530 kg of pigs and barn 2 had 83,250 kg for year 2003 during pump-out. Standard deviation shown in parenthesis.

		H_2S Emissions, mg H_2S m^{-2} hr^{-1}			Literature ranges (see text)
Year	Barn	Before	Max During	After	mg m^{-2} hr^{-1}
2002	1	12.0 (9.4)	1,240.6	3.2 (5.7)	1.6-54
	2	22.9 (13.5)	1,552.8	1.2 (0.7)	
2003	1	25.3 (29.0)	1,478.5	3.8 (1.9)	
	2	65.1 (31.7)	1,184.2	5.4 (2.8)	

		NH_3 Emissions, mg NH_3 m^{-2} hr^{-1}			Literature ranges (see text)
Year	Barn	Before	Max During	After	mg m^{-2} hr^{-1}
2002	1	236.1 (93.7)	1,047.8	289.9 (165.5)	4.8 – 2,376
	2	195.9 (55.8)	1,186.9	348.9 (169.2)	
2003	1	461.6 (129.7)	1,986.7	632.9 (329.1)	Most commonly reported ranges (mg m^{-2} hr^{-1})
	2	679.5 (343.4)	2,334.6	1,008.7 (418.5)	300-500

Table 4. Odor strength and emission levels measured for the pit and tunnel exhaust locations before, during, and after slurry removal. Barn 2 for the 2003 slurry removal event shown. The averages and standard deviations are shown along with the maximum during slurry removal shown in brackets.

	Odor Strength (OU/m^3)			**Odor Emission Rate (OU/m^2-s)**		
Location	Before	During	After	Before	During	After
Pit	1,632 (590)	7,022 (1,215) [9,625]	1,258 (513)	3.4 (1.2)	14.5 (2.5) [19.8]	2.6 (1.1)
Tunnel	2,611 (468)	5,430 (1,237) [8,228]	868 (622)	23.8 (6.5)	77.0 (17.5) [116.6]	2.3 (1.4)

Figure 1. Layout of buildings monitored for this study. Entire site consists of four identical buildings. The monitored buildings shown represent the two center barns of the site. Two pit fans (1,2) one sidewall fan (3), and five endwall tunnel fans (4,5,6,7,8) were used representing four possible emission locations.

Figure 2. (a) Barn temperature, outside temperature, airflow rate and (b) hydrogen sulfide emission before, during, and after a slurry removal event (Barn 1, October 2003 removal event).

Figure 3. (a) Barn temperature, outside temperature, airflow rate and (b) hydrogen sulfide emission before, during, and after a slurry removal event (Barn 2, October 2002 removal event).

Figure 4. Barn airflow rate and ammonia emission before, during, and after a slurry removal event (Barn 2, October 2002 removal event).

Figure 5. Odor strength (a) and (b) odor emission rate from barn 2 during the 2003 slurry removal event. Before data measured on October 14 and “after” data measured on October 27, 2003.

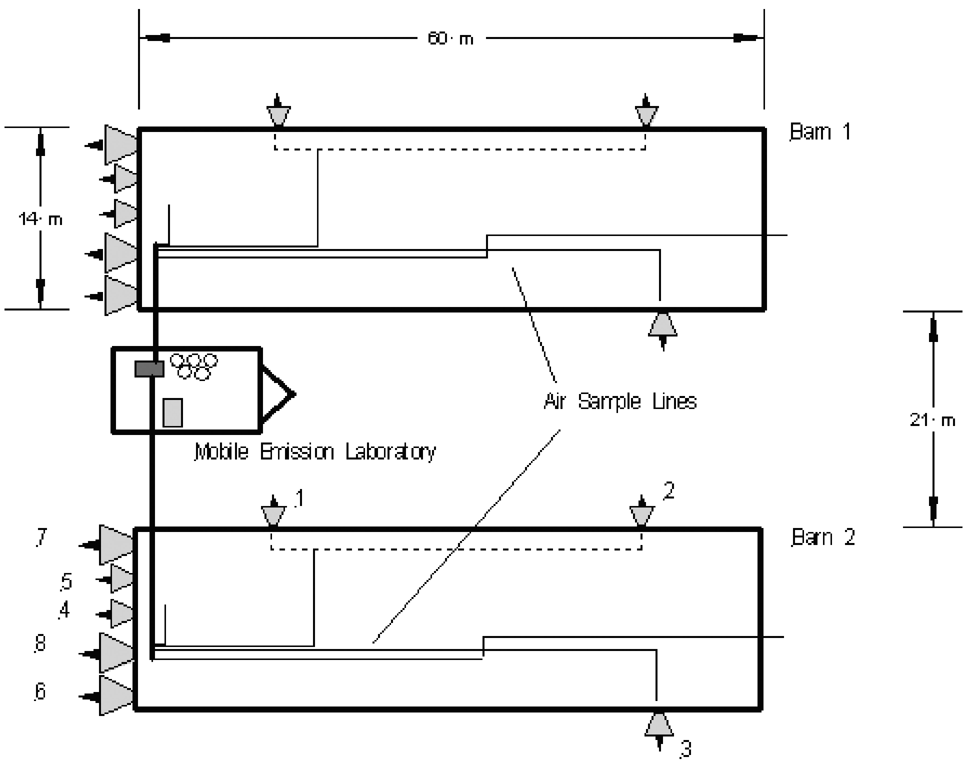
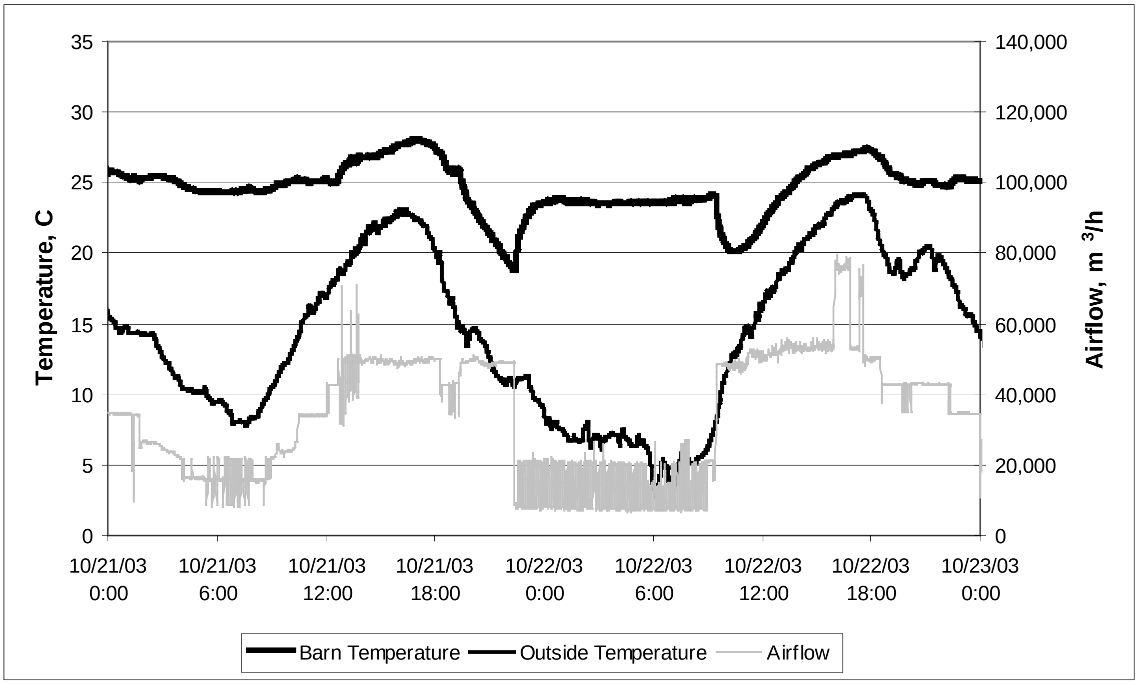
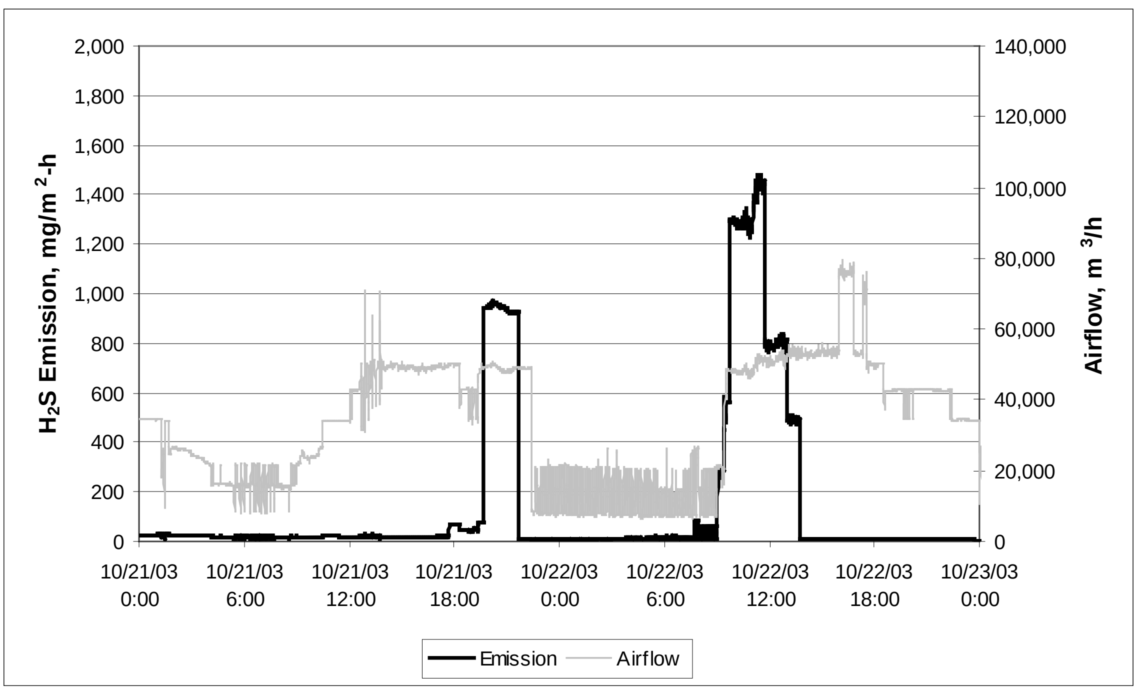

60 m
Barn 1
14 m
Air Sample Lines
21 m
Mobile Emission Laboratory
1
2
Barn 2
7
5
4
8
6
3

Figure 1



Temperature, C
Airflow, m 3/h
35
30
25
20
15
10
5
0
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10/21/03 0:00
10/21/03 6:00
10/21/03 12:00
10/21/03 18:00
10/22/03 0:00
10/22/03 6:00
10/22/03 12:00
10/22/03 18:00
10/23/03 0:00
Barn Temperature
Outside Temperature
Airflow

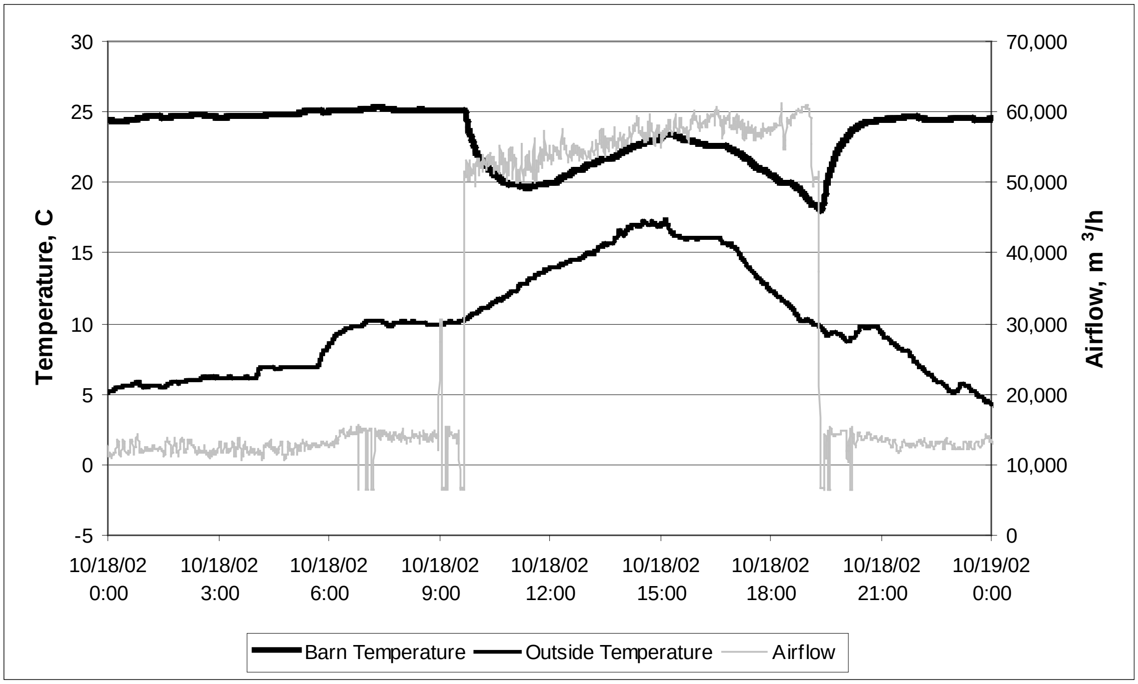
(a)



H2S Emission, mg/m 2-h
Airflow, m 3/h
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10/21/03 0:00
10/21/03 6:00
10/21/03 12:00
10/21/03 18:00
10/22/03 0:00
10/22/03 6:00
10/22/03 12:00
10/22/03 18:00
10/23/03 0:00
Emission
Airflow

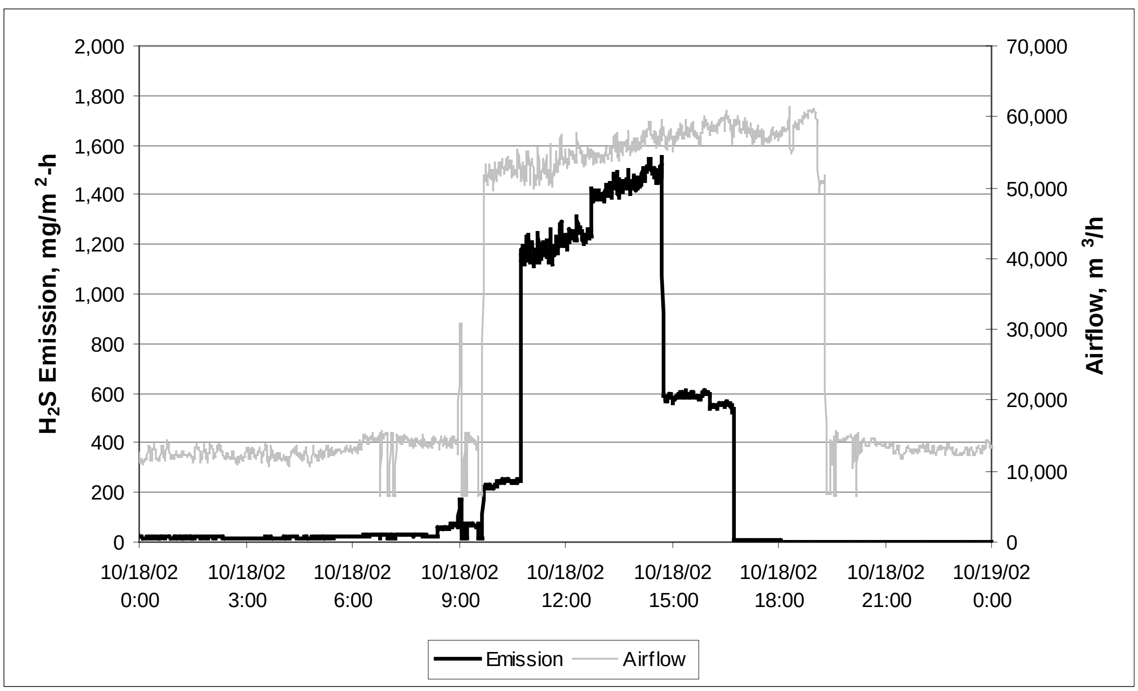
(b)

Figure 2



30
25
20
15
10
5
0
-5
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Temperature, C
Airflow, m 3/h
10/18/02 0:00
10/18/02 3:00
10/18/02 6:00
10/18/02 9:00
10/18/02 12:00
10/18/02 15:00
10/18/02 18:00
10/18/02 21:00
10/19/02 0:00
Barn Temperature
Outside Temperature
Airflow

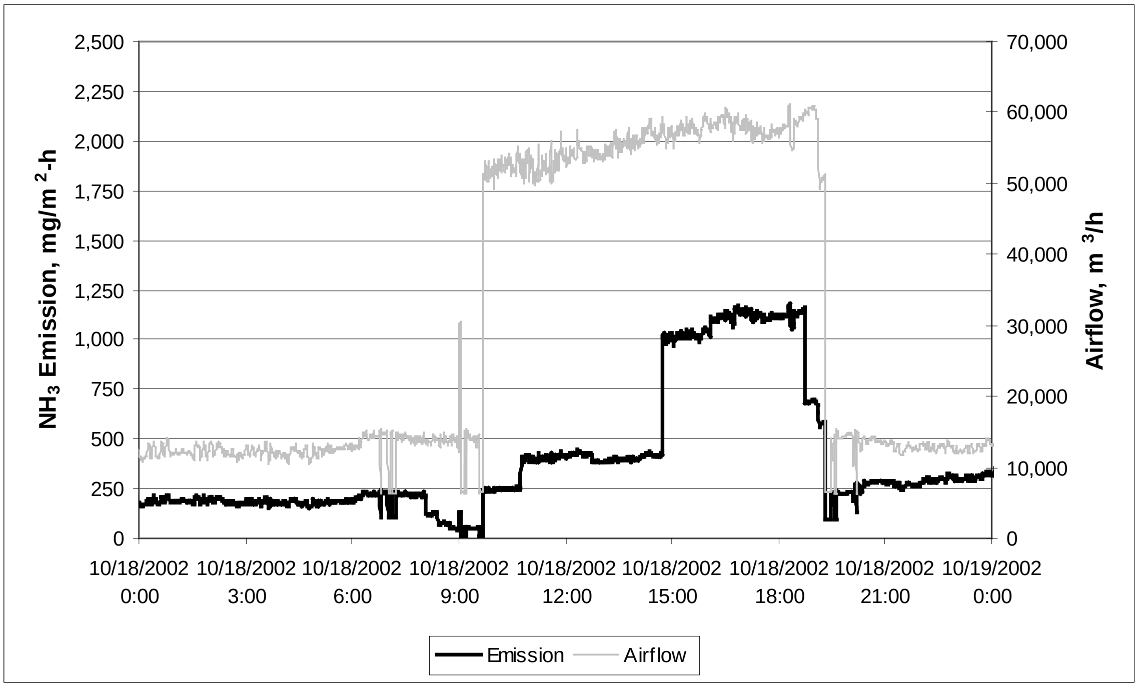
(a)



2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
H2S Emission, mg/m 2-h
Airflow, m 3/h
10/18/02 0:00
10/18/02 3:00
10/18/02 6:00
10/18/02 9:00
10/18/02 12:00
10/18/02 15:00
10/18/02 18:00
10/18/02 21:00
10/19/02 0:00
Emission
Airflow

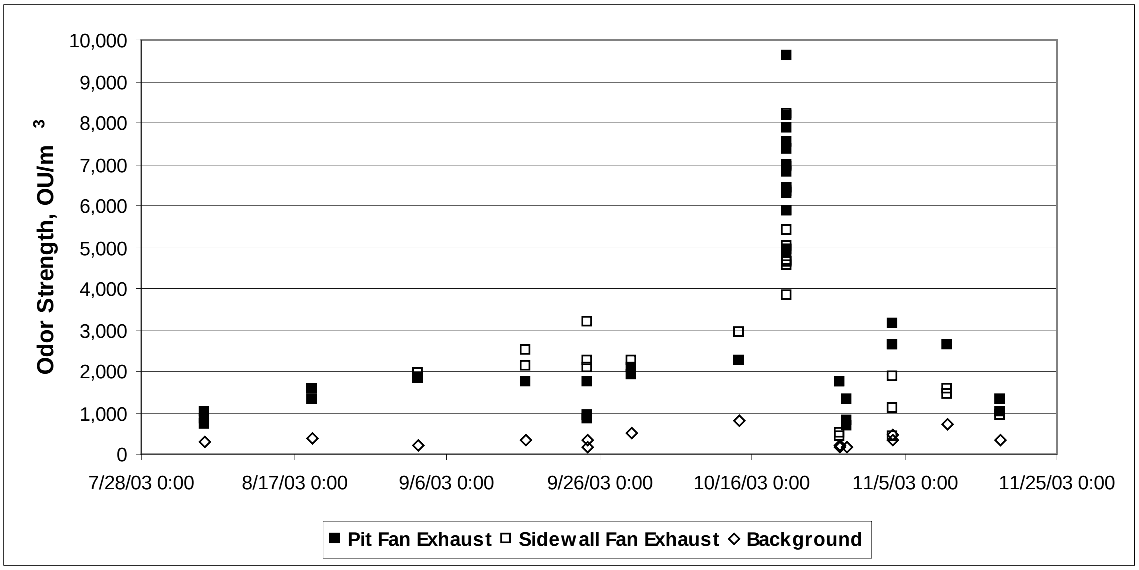
(b)

Figure 3



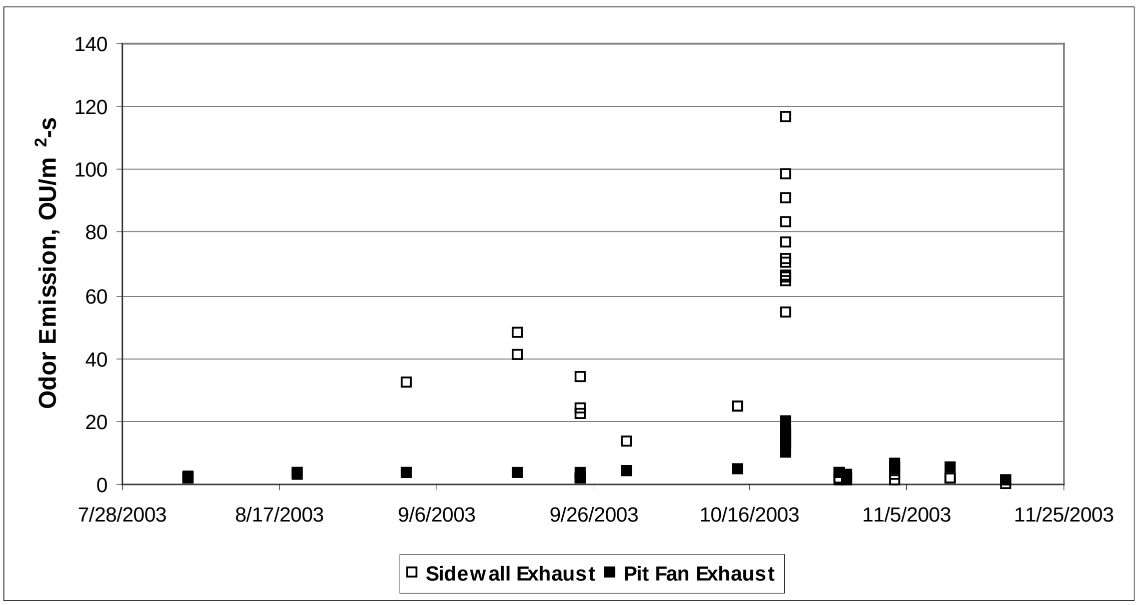
2,500
2,250
2,000
1,750
1,500
1,250
1,000
750
500
250
0
NH3 Emission, mg/m 2-h
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Airflow, m 3/h
10/18/2002 0:00
10/18/2002 3:00
10/18/2002 6:00
10/18/2002 9:00
10/18/2002 12:00
10/18/2002 15:00
10/18/2002 18:00
10/18/2002 21:00
10/19/2002 0:00
Emission
Airflow

Figure 4



Odor Strength, OU/m 3
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
7/28/03 0:00
8/17/03 0:00
9/6/03 0:00
9/26/03 0:00
10/16/03 0:00
11/5/03 0:00
11/25/03 0:00
Pit Fan Exhaust
Sidewall Fan Exhaust
Background

(a)



Odor Emission, OU/m 2-s
140
120
100
80
60
40
20
0
7/28/2003
8/17/2003
9/6/2003
9/26/2003
10/16/2003
11/5/2003
11/25/2003
Sidewall Exhaust
Pit Fan Exhaust

(b)

Figure 5