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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 common practice in the midwestern United States to raise swine in buildings with under-floor slurry storage systems designed to store manure for up to one year. These so-called "deep-pit" systems are 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 (U.S. Department of Agriculture-Initiative for Future Agriculture and Food Systems Project, "Aerial Pollutant Emissions from Confined Animal Buildings"), real-time NH_3 and H_2S with incremental odor emission data were collected for 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-deep concrete pit (or holding tank) below the animal-occupied zone. Results show that the H_2S emission, measured during four independent slurry removal events over two years, increased by an average of 61.9 times relative to the before-removal H_2S emission levels. This increase persisted during the agitation process of the slurry that on average occurred over an 8-hr time period. At the conclusion of slurry agitation, the H_2S emission decreased by an average of 10.4 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 inside the pig building and emissions from this facility. H_2S is the gas of most concern and can reach levels dangerous to animals and workers. These results highlight the need for a preplanned protocol that must be established for barn ventilation rate maintenance to ensure that H_2S concentrations do not reach lethal levels.

INTRODUCTION

Many swine raised (reared from 7 or 18 kg to 120 kg) in the midwestern U.S. are grown 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 liquid manure fertilizer. 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 three 8-hr work days per 1000-pig building 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 process if proper ventilation procedures are not followed. Turbulent activity of the slurry surface can result in very rapid release of odors, ammonia (NH_3), and hydrogen sulfide (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 two identical deep-pit swine finishing facilities located in the midwestern part of the United States over two annual slurry removal events.

Swine Housing NH_3 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 volatile organic compounds 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 because of 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 animal unit [AU]$^{-1}$ day^{-1}; 1 AU = 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 attributed 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 ~20% for a period of 10 hr, 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} yr^{-1} (160 g NH_3 AU^{-1} day^{-1} or 1008 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 1-yr 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 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 restocked 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 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 3751 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 pig^{-1} hr^{-1} (38 kg average pig wt) to 210 g NH_3 pig^{-1} hr^{-1} (83 kg average pig wt) 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} sec^{-1} (311 g NH_3 AU^{-1} day^{-1} or 2376 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 ~5 μg NH_3 m^{-2} sec^{-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} sec^{-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}

sec^{-1} (23–160 g NH_3 AU^{-1} 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} sec^{-1} (10–26 g NH_3 AU^{-1} 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} sec^{-1} (28–80 g NH_3 AU^{-1} 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-week 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 kg NH_3 AU^{-1} yr^{-1} (30 g NH_3 AU^{-1} day^{-1}).

Swine Housing H_2S 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 1492 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 restocked 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} sec^{-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 ~2 μg H_2S m^{-2} sec^{-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 ~5 μg H_2S m^{-2} sec^{-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} sec^{-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 ~10 μg H_2S m^{-2} sec^{-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} sec^{-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 various swine production buildings has been reported. Considering the literature cited, the range of H_2S emissions expected for finishing pigs is between 1.6 and 54 mg H_2S m^{-2} hr^{-1} from the exhaust ventilation air for swine finishing pigs. The range of NH_3 emissions expected is between 4.8 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 to 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 three-fold 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; 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 Initiative for Future Agriculture and Food Systems program.[12,13] Each facility monitored, as shown in Figure 1, was designed to house 1000 pigs ranging in weight between ~18 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 manure for one calendar year. Slurry removal and land application was conducted once per year in the fall (October).

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; Figure 1) in combination with a series of 10 rectangular center-ceiling inlets to distribute fresh air within the building. Figure 1 shows the center-ceiling inlet placement and the approximate airflow patterns desired from these inlets. 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 by operation of the end wall exhaust fans and 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 and pertinent environmental data and to monitor the barn ventilation rate. NH_3 (Model 17C chemiluminescence; TEI, Inc.), H_2S (Model 45C pulsed fluorescence; TEI, Inc.), and CO_2 (Model 3600 IR, MSA, Inc.) were measured at 12 locations: six from Barn 1 and six from Barn 2. A solenoid switching system enabled gas samples to be delivered to each analyzer simultaneously in 10-min switching increments. Therefore, each location was measured for 10 min every 120 min. The gas concentration measurement at the conclusion of each 10-min sampling interval was used to represent the concentration at that sampling location for

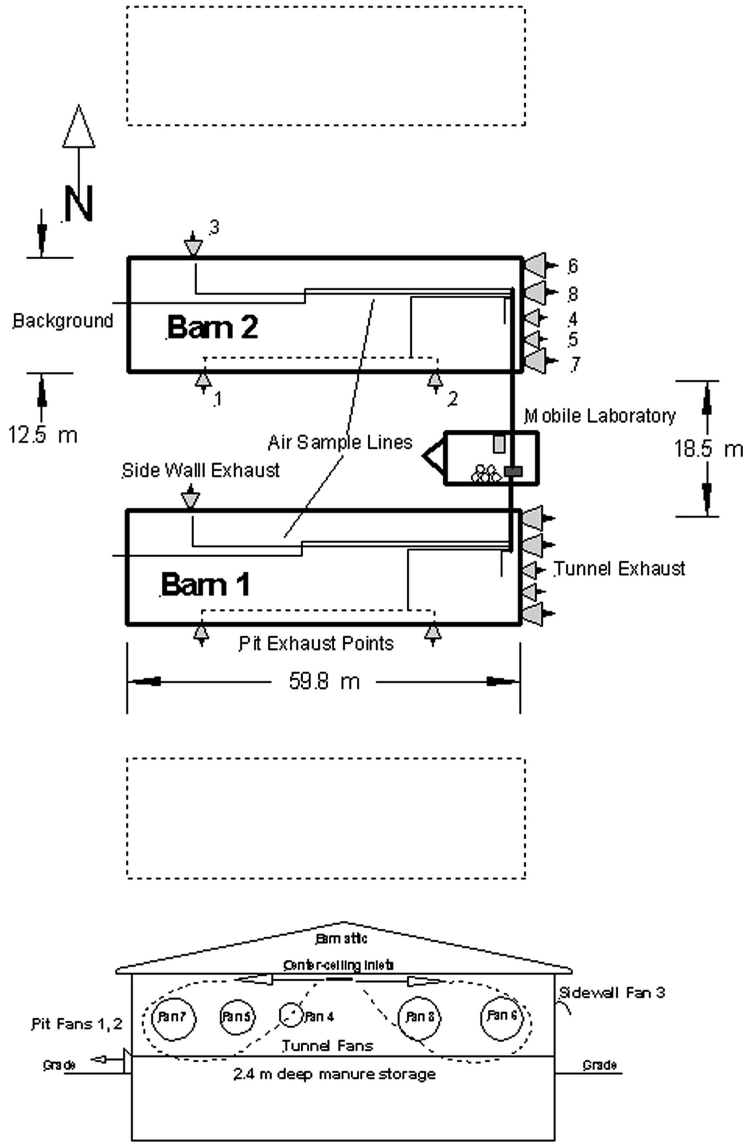

Figure 1. Layout of buildings monitored for this study. Entire site consists of four identical buildings. The monitored buildings shown represent the two center barns of the site. Two pit fans (1,2), one sidewall fan (3), and five end wall tunnel fans (4,5,6,7,8) were present, representing four possible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

the prior 120 min. This enabled a continuous concentration profile at each sampling location that was used along with continuous airflow data to generate a continuous emissions profile. The analyzers were calibrated before each pump-out event with U.S. Environmental Protection Agency (EPA)-protocol calibration gases. Environmental variables such as temperature, relative humidity, static pressure, and end wall curtain opening level were also measured. 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.[14] The FANS unit was a device that fit on the intake side of all fans and integrated air velocity across the intake area of the fan with five calibrated anemometers. Airflow rates were measured for a range of expected operating static pressures and fan rpm levels from which a fan calibration equation was developed. By knowing fan status and/or fan rpm level and the current operating static pressure, fan airflow rate could be determined. Specific details related to the MEL setup and quality assurance/quality control procedures can be found in Heber et al.[13] and Jacobson et al.[15]

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). Concentrations from the other three sampling points were also monitored, but these were not included in the emission calculations. Emission rates were calculated as

$$E = \Sigma(Q_o C_o - Q_i C_i) = \Sigma(Q'_o C'_o - Q'_i C'_i) \qquad (1)$$

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[a]	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

[a]Barn 1 in 2003 emptied in two separate events over a two-day period.

where C_i is mass concentration at the barn air inlet, mg m^{-3} or μg m^{-3}; E is barn emission rate, mg sec^{-1} or μg sec^{-1}; C_o is mass concentration at the barn air exhaust, mg m^{-3} or μg m^{-3}; C_i' is standardized mass concentration at the barn air inlet (based on standard conditions of temperature and pressure [STP]), mg $(sm)^{-3}$ or μg $(sm)^{-3}$; C_o' is standardized mass concentration at the barn exhaust (based on STP), mg $(sm)^{-3}$ or μg $(sm)^{-3}$; Q_o is barn outlet moist airflow rate at T_o, m^3 sec^{-1}; Q_i is barn inlet moist airflow rate at T_i, m^3 sec^{-1}; Q_i' is moist standard ventilation rate at the barn inlet (based on STP), sm^3 sec^{-1}; and Q_o' is moist standard ventilation rate at barn exhaust (based on STP), sm^3 sec^{-1}.

The background concentrations were measured also with one of the sampling locations from a total of six for each monitored barn. The background sampling location was measured within 0.5 m of the end of each barn as shown in Figure 1. The STPs used were 20 °C and 101,325 Pa.

Odor data were also collected for this research project on 2-week intervals. However, during slurry agitation and manure removal, frequent gas samples were collected before, during, and after slurry removal to assess odor concentration and odor emission rate. Odor samples were collected in 10-L Tedlar bags using a vacuum chamber (Model Vac-U-Camber; SKC, Inc.) with a vacuum pump (Model 224–44XR; SKC, Inc.) at a sample flow rate of 3 L min^{-1}. Odor samples were analyzed within 18 hr using a dynamic dilution forced-choice olfactometer (Model AC'SCENT; St. Croix Sensory, Inc.) at the Iowa State University Olfactometry Laboratory.

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 the 24 hr surrounding these slurry removal events. The producer 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 30 fresh-air changes per hour, open all 10 center-ceiling inlet diffusers, and make sure that the end wall curtain used for tunnel ventilation was closed. After these adjustments were made, usually more than 1 hr 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 6.25–8.5 hr as shown in Table 1.

Table 2. H_2S concentration (ppb) before, during, and after slurry removal.

Year	Barn	Before	Max During	After	Date	Location
2002	1	272	9990[a]	79	October 16, 2002	pit
		592	9833	197	October 16, 2002	sidewall
		473	9990[a]	186	October 16, 2002	tunnel
	2	1084	5455	31	October 18, 2002	pit
		1775	11,990	43	October 18, 2002	sidewall
		857	15,918	30	October 18, 2002	tunnel
2003	1[b]	397	850	467	October 21, 2003	pit
		467	22,245	69	October 22, 2003	pit
		336	3128	678	October 21, 2003	sidewall
		678	12,011	71	October 22, 2003	sidewall
		337	11,957	148	October 21, 2003	tunnel
		148	16,378	71	October 22, 2003	tunnel
	2	2067	35,825	93	October 20, 2003	pit
		460	7840	55	October 20, 2003	sidewall
		1360	8075	69	October 20, 2003	tunnel

[a]Exceeded maximum set range of analyzer, which was 10,000 ppb. Analyzer subsequently changed to a range of 50,000 ppb; [b]Barn slurry emptied over two days; after on October 21, 2003, the same as before on October 23, 2003.

RESULTS AND DISCUSSION

The results presented summarize the H_2S, NH_3, 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 2 yr 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 hr 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 location during the 2003 removal event. On average, the H_2S concentration measured at the pit fan exhaust location reached a level that was 18 times higher during agitation as compared with 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 with 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 and 8 °C for October 21, 2003, and a high/low of 24 and 3 °C for October 22, 2003, respectively. The producer routinely bypassed the barn's automatic control system during a slurry removal event to ensure an adequate ventilation rate for the barn

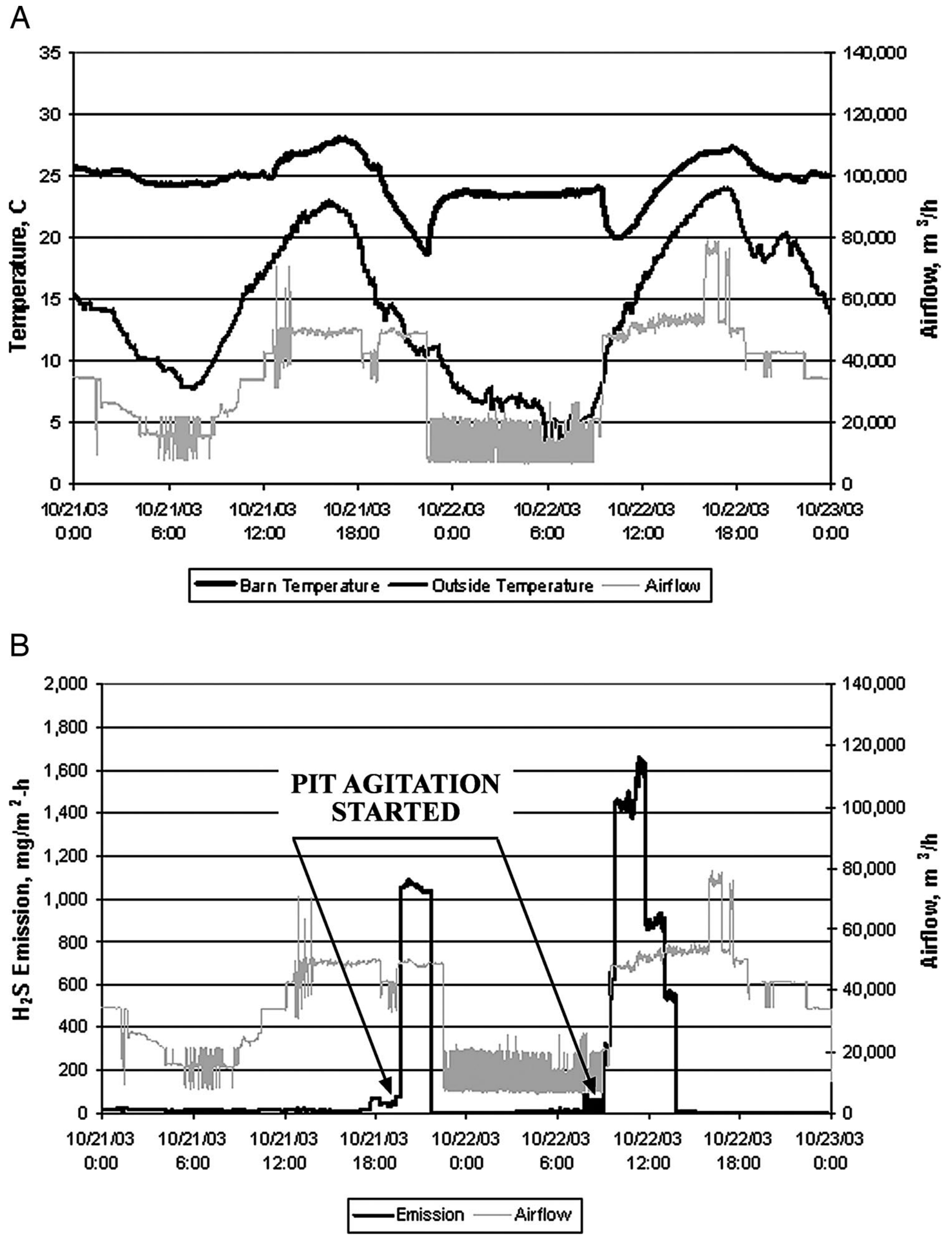

Figure 2. (a) Barn temperature, outside temperature, airflow rate, and (b) H_2S emission before, during, and after a slurry removal event (Barn 1, October 2003, removal event).

by manually turning on selected tunnel fans. The elevated ventilation rate initiated by the producer 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 after the slurry was agitated and fell quickly once slurry agitation stopped. Observing the H_2S analyzer once agitation began showed a definite elevated concentration within minutes after the agitator was started. 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}. The barn, running in automatic control, would have ventilated the space at ~13,200 m^3 hr^{-1} or 6.5 fresh-air changes per hr. With the producer's manual override of the ventilation system, the barn was allowed to ventilate at 56,000 m^3 hr^{-1} or 27.9 fresh-air changes per hr. This characteristic points out the need for the establishment of a ventilation protocol before considering the agitation of slurry, regardless of the depth of slurry in the holding pit. The producer's protocol resulted in no loss of pig life for any of the pit agitation procedures studied with this research project.

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

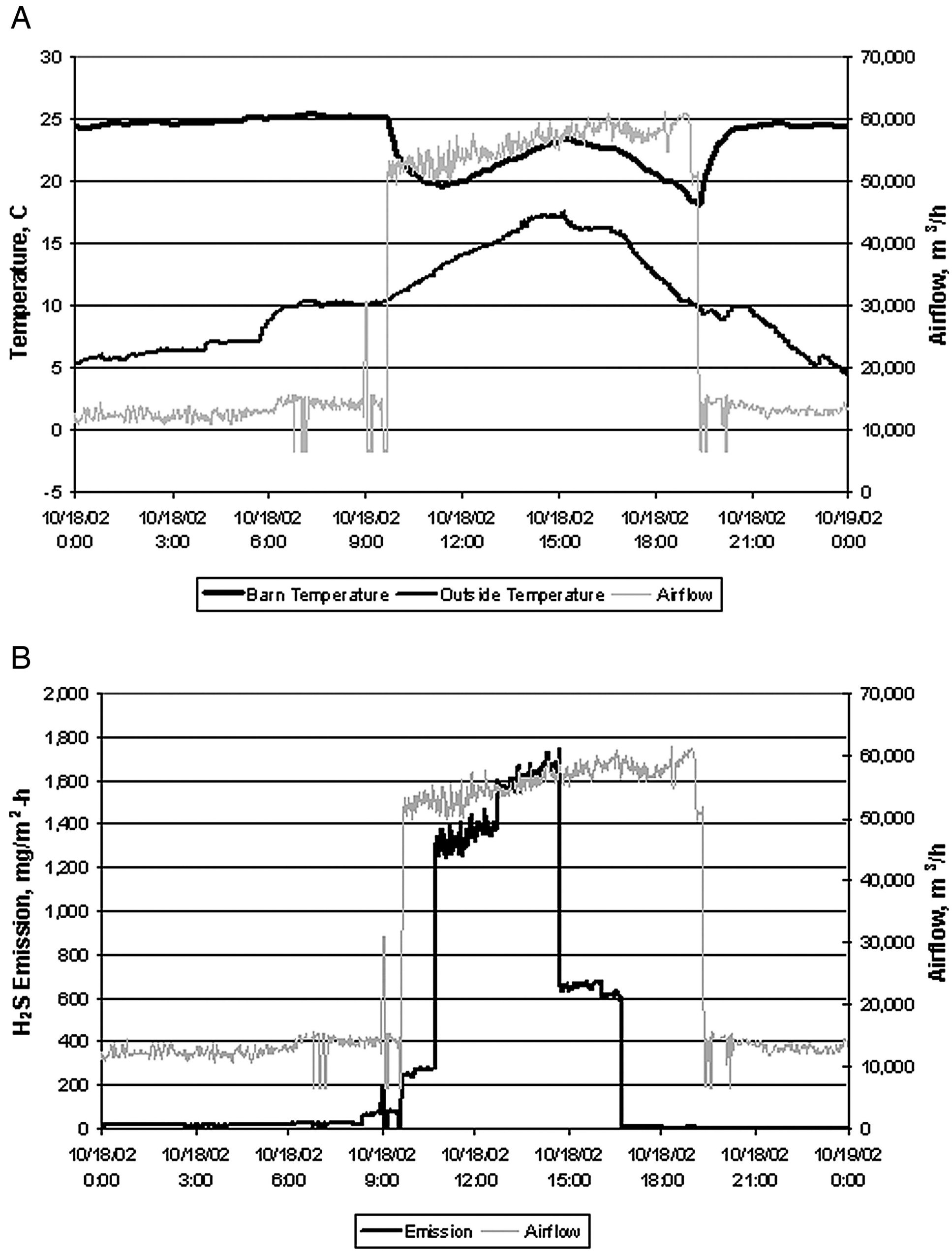

Figure 3. (a) Barn temperature, outside temperature, airflow rate, and (b) H_2S emission before, during, and after a slurry removal event (Barn 2, October 2002, removal event).

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 1,739 mg H_2S m^{-2} hr^{-1}. The average H_2S emission rate for the four slurry removal events was 1,528 ± 201 mg H_2S m^{-2} hr^{-1}. The average before and after H_2S emission rate for the four slurry removal events was 35.1 ± 26 mg H_2S m^{-2} hr^{-1} and 3.8 ± 1.9 mg H_2S m^{-2} hr^{-1}, respectively. If one considers the period of time from just before slurry agitation to the time just after all of the manure was removed from the barn, the cumulative H_2S emission measured for the case shown in Figure 2b was 5.5-kg H_2S and that shown in Figure 3b was 5.7-kg H_2S. The average NH_3 emission rate for the four slurry removal events was 1,836 ± 708 mg NH_3 m^{-2} hr^{-1}. The average before and after NH_3 emission rate for the four slurry removal events was 441 ± 251 mg NH_3 m^{-2} hr^{-1} and 639 ± 369 mg NH_3 m^{-2} hr^{-1}, respectively. Consistently, the after-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 single continuous slurry removal event shown in Figure 3.

Odor data were collected for this research project at 2-week intervals. However, during the slurry removal event for Barn 2 in 2003, a more detailed odor evaluation procedure was conducted to capture the odor emitted during slurry agitation and manure removal. Odor data for Barn 1 during slurry removal were not collected. Table 4 and Figure 5 summarize the measured

Table 3. Measured emission levels for H_2S and NH_3 in mg m^{-2} hr^{-1}.[a]

H_2S Emissions, mg H_2S m^{-2} hr^{-1}					Literature ranges (see text) mg m^{-2} hr^{-1} 1.6–54
Year	Barn	Before	Max During	After	
2002	1	13.5 (10.5)	1389.4	3.6 (6.4)	
	2	25.6 (15.1)	1739.1	1.3 (0.8)	
2003	1	28.3 (32.5)	1655.9	4.3 (2.1)	
	2	72.9 (35.5)	1326.2	6.0 (3.1)	
NH_3 Emissions, mg NH_3 m^{-2} hr^{-1}					Literature ranges (see text) mg m^{-2} hr^{-1} 4.8–2376
Year	Barn	Before	Max During	After	
2002	1	264.4 (105.0)	1173.5	324.7 (185.3)	
	2	219.3 (62.5)	1329.3	390.8 (189.5)	
2003	1	516.9 (145.3)	2225.0	708.8 (368.6)	Most commonly reported ranges (mg m^{-2} hr^{-1}) 300–500
	2	761.0 (384.6)	2614.7	1129.8 (468.7)	

Notes: [a]Both barns had a floor area of 747 m^2. Barn 1 had 58,900 kg of pigs, and Barn 2 had 52,500 kg for year 2002 during slurry removal. Barn 1 had 103,530 kg of pigs, and Barn 2 had 83,250 kg for year 2003 during slurry removal. Standard deviation shown in parenthesis.

results. The increase in odor concentration, mgasurgd in odor units (OU) defined as the fesh-air dilution-to-detection (OU m^{-3}) during slurry removal was 4.3 and 2.1 times higher for the pit and tunnel fan exhaust locations, respectively, compared with the before-removal levels. The after-removal odor concentration was 1.3 and 3 times lower than the before-removal levels. The maximum odor strength during slurry removal reached 9,625 OU m^{-3} and 8,228 OU m^{-3} for the pit and tunnel exhaust locations, respectively. During slurry agitation, the odor emission rate (OU m^{-2} sec^{-1}) had maximum levels of 22.2 and 130.6 OU m^{-2} sec^{-1} for the pit and tunnel exhaust fan locations, respectively. The odor concentration measurements indicated that the pit and tunnel exhaust points were relatively similar before, during, and after slurry removal. However, the odor emission was 5.3 times higher from the tunnel exhaust point than the pit exhaust point because of the higher airflow rate from the tunnel exhaust fans during slurry removal.

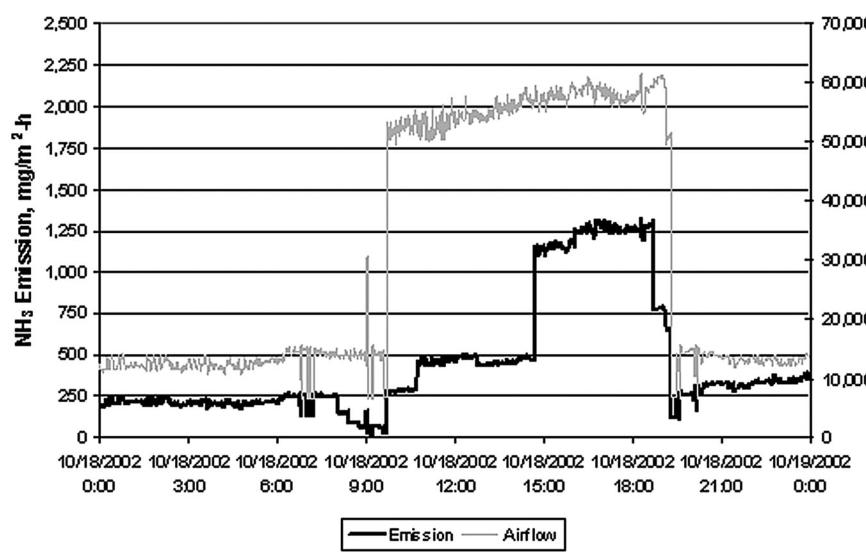

Figure 4. Barn airflow rate and NH_3 emission before, during, and after a slurry removal event (Barn 2, October 2002, removal event).

Table 4. Odor strength (OU m^{-3}) and odor emission rate (OU m^{-2} s) measured for the pit and tunnel exhaust locations before, during, and after slurry removal. Barn 2 for the 2003 slurry removal event shown.

	Odor Strength (OU m^{-3})			Odor Emission Rate (OU m^{-2} s)		
Location	**Before**	**During**	**After**	**Before**	**During**	**After**
Pit	1632 (590)	7022 (1215) [9625]	1258 (513)	3.8 (1.4)	16.2 (2.8) [22.2]	2.9 (1.2)
—	{1.7 m^3 sec^{-1}}	{1.7 m^3 sec^{-1}}	{1.7 m^3 sec^{-1}}			
Tunnel	2611 (468)	5430 (1237) [8228]	868 (622)	26.7 (7.3)	86.2 (19.6) [130.6]	2.5 (1.6)
—	{7.6 m^3 sec^{-1}}	{11.9 m^3 sec^{-1}}	{2.3 m^3 sec^{-1}}			

Notes: The average and standard deviation (in parentheses) shown along with the maximum (in brackets) during slurry removal. The average airflow rate (in {}) is also shown for the measurements before, during, and after slurry removal. These are shown below each odor strength measurement.

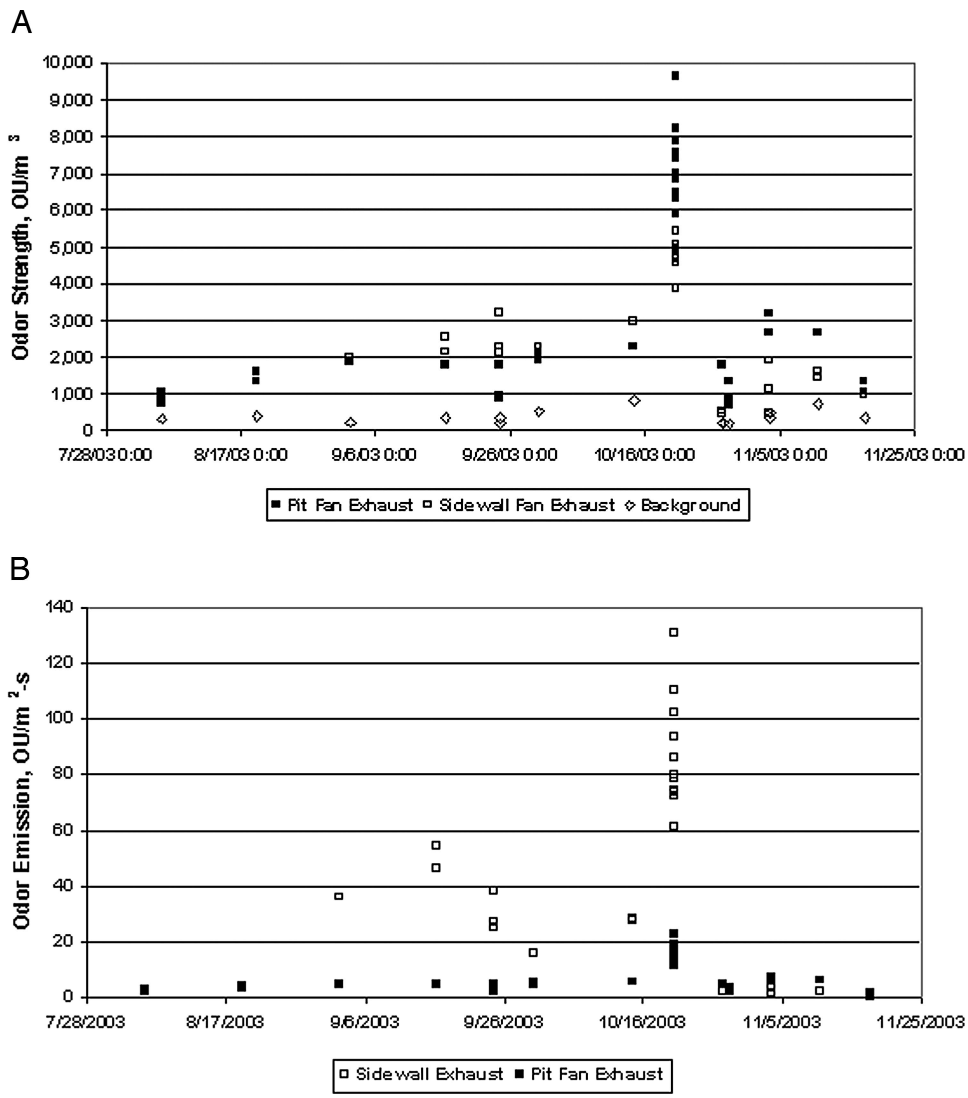

Figure 5. (a) Odor strength and (b) odor emission rate from Barn 2 during the 2003 slurry removal event. Before data measured on October 14, 2003, and after data measured on October 27, 2003.

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 preremoval 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 because of 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 should be established before agitation begins, and all workers should remain outside the facility during agitation. For this research project, the operator established a fixed and minimum ventilation rate of ~27 fresh-air changes per hour with the resulting inside H_2S concentration levels well below lethal levels.

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