Screening Ventilation Strategies for Confined-Space Manure Storage Facilities

E. P. Pesce, J. Zhao, H. B. Manbeck, D. J. Murphy

ABSTRACT. *Fatalities associated with entry into on-farm confined-space manure storage facilities occur each year. The fatalities are due to asphyxiation or poisoning by exposure to high concentrations of hydrogen sulfide, methane, and carbon dioxide. Forced ventilation has been shown to be an effective way to reduce concentrations of noxious gases to levels that are safe for human entry into these storage facilities. Hydrogen sulfide (H_2S) was used as an indicator gas to investigate the effectiveness of forced-air ventilation strategies for eliminating the toxic and oxygen-deficient atmosphere in confined-space manure storage facilities. This article focuses on experimental methods for identifying ventilation strategies that effectively reduce toxic gas (i.e., H_2S) concentrations in a fan-ventilated confined-space manure tank to the OSHA permissible exposure limit (PEL) (H_2S PEL = 10 ppm) and to 25% of the initial gas concentration. Typical H_2S concentration reduction curves during forced-air ventilation were identified in the tank as well. Based on the experimental tests conducted in this research, the most promising candidate ventilation strategies were identified for this rectangular confined-space manure tank with solid, fully slotted, and partially slotted covers. In addition, based on the results of experimental tests, a field-based database was developed for future validation of computational fluid dynamics modeling protocols.*

Keywords. Confined-space manure storage facilities, Forced-air ventilation, Hydrogen sulfide, OSHA permissible exposure limit, Safety, Ventilation strategy.

The Occupational Safety and Health Administration's definition of a confined space is one that: "(1) is large enough and so configured that an employee can bodily enter and perform assigned work; (2) has limited or restricted means for entry or exit; and (3) is not designed for continuous employee occupancy" (OSHA, 2004). Entry into confined-space manure storage facilities is considered a major safety concern in the agricultural industry because of the potential for multiple fatalities within a single incident. For example, the loss of life of four members of one family, plus a hired employee, occurred recently in Virginia when one person entered the manure transfer area to unplug a pipe, and four more followed as would-be rescuers (Fox News, 2007). The most hazardous gases produced in manure storage facilities include ammonia (NH_3), hydrogen sulfide (H_2S), methane (CH_4), and carbon dioxide (CO_2). In this research, hydrogen sulfide was used as the indicator gas to identify the most effective ventilation strategy from a candidate list of ventilation strategies for removing noxious gases from a rectangular manure tank.

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Hydrogen sulfide can be identified easily by a rotten-egg smell in relatively low concentrations (<5 ppm). It is heavier (density = 1.54 kg m^{-3} at 0°C) than air (1.29 kg m^{-3} at 0°C), so it tends to accumulate at the bottom of poorly ventilated confined-space manure storage facilities. Breathing hydrogen sulfide deadens the sense of smell after an initial strong exposure (OSHA, 1995). For example, at 150 to 250 ppm, the olfactory nerve is paralyzed after a few inhalations, and the sense of smell expires. At 530 to 1000 ppm, strong stimulation of the central nervous system leads to respiratory paralysis with only a few breaths. At concentrations approaching 1000 ppm or more, unconsciousness can occur within seconds and death within minutes (Durand, 2006). The release of high concentrations of toxic hydrogen sulfide gas can occur during agitation of manure (Groves and Ellwood, 1991; Patni and Clarke, 1991). Hoff et al. (2006) studied emissions of ammonia, hydrogen sulfide, and odor before, during, and after slurry removal from a swine in-building deep-pit. The results show that H_2S emissions during slurry removal increased by an average of 61.9 times relative to the H_2S emission levels before removal. This increase persisted during the manure agitation.

The atmosphere generated within confined-space manure storage facilities creates very hazardous conditions for farmers who may need to enter these manure storage facilities to perform equipment maintenance, repairs, or to retrieve objects that have fallen into the facility. Beaver and Field (2007) documented fatalities in livestock manure storage facilities and handling facilities from 1975 to 2004. One result from this analysis of 77 fatality cases showed that the death rate per year increased between 1975 and 2004: 1.6 from 1975 through 1984; 2.7 from 1985 through 1994; and 3.5 from 1995 through 2004. Tragically, when injuries occur in confined-space manure storage facilities, they likely involve multiple fatalities (Murphy and Steel, 2001).

The Occupational Safety and Health Administration (OSHA) developed the confined-space regulations documented in the 29 Code of Federal Regulations (CFR), Part 1910.146. Agriculture is exempted from OSHA's confined-space regulations. However, the consequence of unsafe entry into confined-space manure storage facilities requires that safety and health personnel have a duty to mitigate these hazardous conditions. OSHA's confined-space regulations provide a nationally accepted guideline for safe entry into confined spaces and are used in this research as well. The regulations for permit-required confined spaces (OSHA, 2004) require that the internal atmosphere within a confined space be tested for oxygen levels, flammable gases and vapors, and potential toxic air contaminants prior to human entry. Forced-air ventilation must be used when the gas concentrations exceed their permissible levels. OSHA standards also indicate that an employee may not enter a confined space without a self-contained breathing apparatus (SCBA) until forced-air ventilation has eliminated any existing hazardous atmosphere. Thus, it is imperative that confined spaces be properly ventilated prior to entry.

However, research studies on safety ventilation in confined-space manure storage facilities are limited. For example, some comprehensive research was conducted on measuring H_2S emissions in swine buildings with underfloor manure pits (Ni et al., 2000; Ni et al., 2002; Lim et al., 2004) during ventilation. But none of these researchers studied ventilation strategies for safe entry and gas evacuation during forced ventilation. Lloyd (2000) studied ventilation of a manure storage facility adjacent to a swine housing facility. In his research, the airflow entry location was fixed and the manure storage facility cover was solid. These limitations in Lloyd's research were overcome by this research. In this research, a rectangular confined-space manure tank was used to identify the best ventilation strategy from several ventilation strategies for each of three cover types (i.e., solid, fully slotted, and partially slotted). The H_2S concentrations in the

airspace of the manure tank during agitation and ventilation were monitored. Alternative fan locations, cover types, and airflow rate were also considered in this study.

The goals of this research were (1) to identify the best ventilation strategies for a rectangular confined-space manure tank for each of three cover types (i.e. solid, fully slotted, and partially slotted) for reducing H_2S concentration to the OSHA permissible exposure limit (PEL) level (10 ppm) (OSHA, 1995), and (2) to develop a database of H_2S concentration reduction curves during forced-air ventilation of the confined-space manure tank. The OSHA specific limit for H_2S is based on an 8 h time-weighted average (TWA) exposure.

Experimental System Design

The manure storage facility used for real-time measurements of H_2S concentrations in this study was a rectangular confined-space swine slurry tank (fig. 1) located at the Penn State Swine Research Center. The tank was installed inside a 6.71 m diameter by 4.58 m high cylindrical steel manure storage facility (fig. 2). The dimensions of the rectangular tank were 5.49 m (L) $\times$ 2.74 m (W) $\times$ 1.83 m (H). The 1.83 m airspace height above the manure surface was maintained by partially filling the tank with swine manure to a depth of 2.75 m. Slotted wood decking completely covered the manure tank. The facility was equipped with a submersible hydraulic pump located on the west end of the manure tank. The pump was connected to a hoist located on the cover decking to allow for easy access to the pump for maintenance purposes. The pump, when engaged, agitated the manure to obtain high concentration levels of H_2S in the confined airspace. The agitation ceased as soon as the ventilation commenced. The effectiveness of each studied ventilation strategy was evaluated based on the time required to reduce the initial H_2S concentration level to the OSHA PEL level (T_{pel}, 10 ppm) and to 25% of the initial concentration (T_{25}).
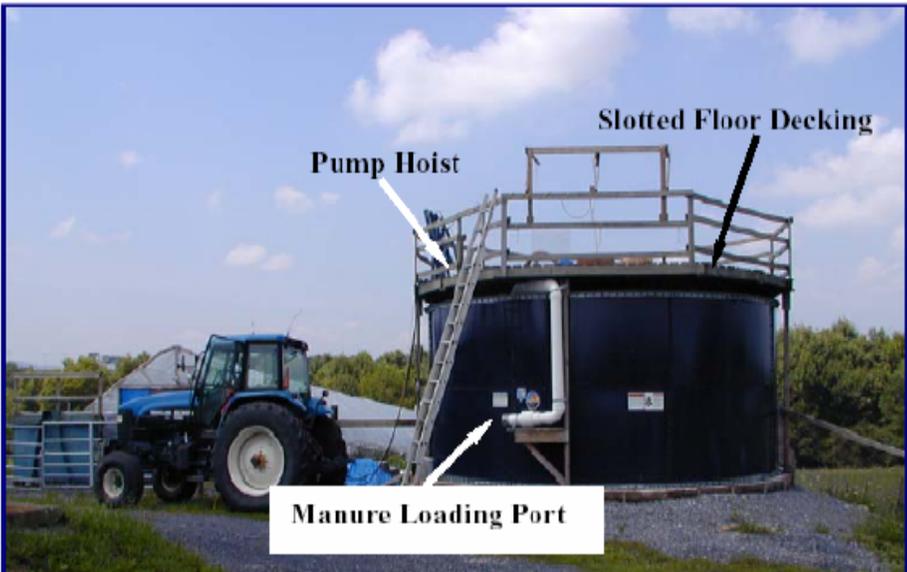

Figure 1. Test facility located at the Penn State Swine Research Center.
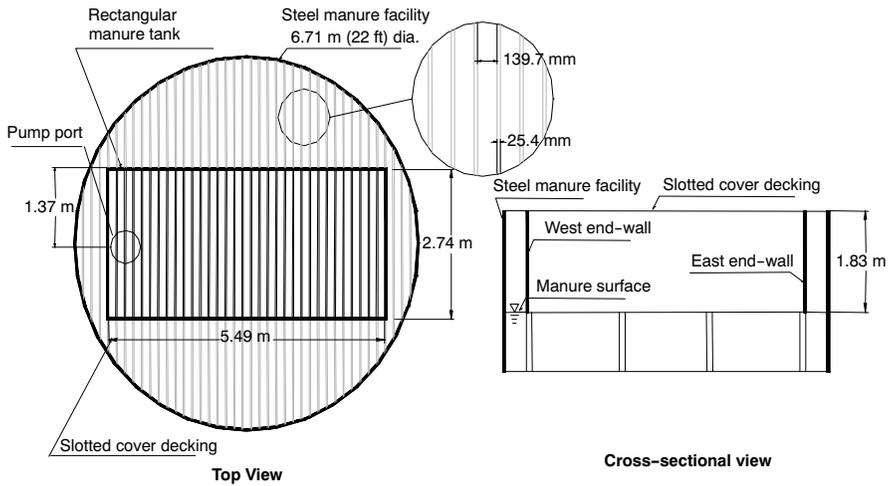
Figure 2. Rectangular confined-space manure tank geometry.

(a) Fully slotted cover system

(b) Partially slotted cover system
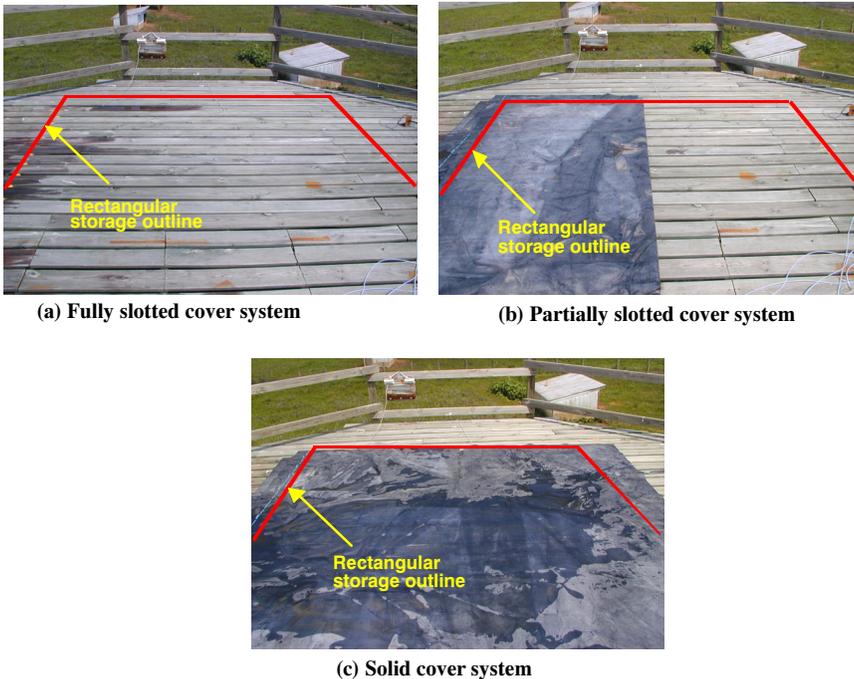

(c) Solid cover system

Figure 3. Cover types at test facility.

The original cover treatment was fully slotted (fig. 3a). The fully slotted cover was converted to a partially slotted cover by covering half of the width of the slotted cover using rubber roofing material (fig. 3b). The rubber roofing material covered the entire width and length of the rectangular tank decking to create the solid cover system (fig. 3c). Applying weights to the rubber roofing material provided resistance against upward air

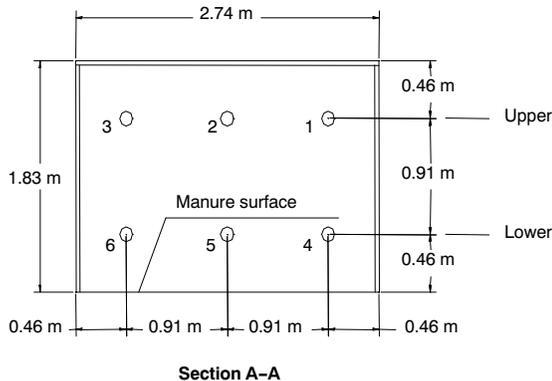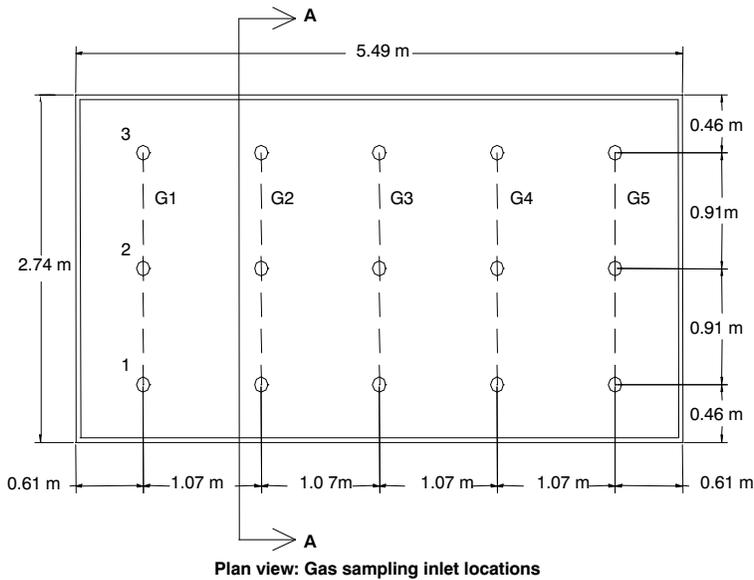**Plan view: Gas sampling inlet locations**

Section A–A

Figure 4. Gas sensor inlet locations for real-time measurements at the five grids (G1 to G5) at the upper (U) and lower (L) levels at the confined-space manure tank test.

pressure from the confined airspace during forced ventilation. Sealing the slots between the wood planks and rubber roofing material along the boundaries of the rectangular tank with polyurethane foam insulation material provided a closed system by minimizing unwanted air exfiltration around the boundary.

Gas Monitoring and Control System

Project budget considerations limited the number of gas monitors to two AreaRAE multi-gas monitors (RAE Systems, 2002) for measuring real-time gas concentrations within the confined airspace. A solenoid switching system to monitor several locations with one monitor resolved this limitation. One monitor measured the upper level gas concentrations, while the other measured the lower level gas concentrations (fig. 4,

section A-A). The AreaRAE multi-gas monitor has the capacity to measure concentrations of H_2S from 0 to 100 ppm (1 ppm resolution). The monitor communicates with and transmits readings to a computer on a real-time basis through a wireless, radio-frequency modem. It is capable of transmitting real-time gas concentration data to a computer located up to 3.6 km from the test facility. A sensing grid for real-time data collection measured the spatial distribution of H_2S concentrations across the confined airspace before, during, and after manure agitation and during forced-air ventilation after agitation ceased. Figure 4 displays the dimensional layout of the gas sensing grids along the length and width of the confined-space manure tank. The monitors were connected to the sampling locations with Teflon tubing with 2.38 mm (3/32 in.) ID and 3.97 mm (5/32 in.) OD. This tubing has high durability and resistance to staining by high concentrations of noxious gas.

Each monitor was able to measure the gas concentrations at three sampling locations through the solenoid switching system. Figure 5 shows the connection detail between the sampling locations (1 to 3 = upper level; 4 to 6 = lower level), solenoid switches, gas monitors (AreaRAE), and an auxiliary pump. Each monitor was equipped with an internal 400 cm³ min⁻¹ capacity vacuum purging pump, and each monitor was connected to four 2-way solenoid switches (A, B1, B2, B3). Three of the solenoids switched between the sampling and purging lines. Another solenoid (A) switched between the gas monitor and a fresh air source. The auxiliary pump continuously purged air from each sampling location that was not purged by the monitor. While the monitor sampled from a specific location, the auxiliary pump purged air from the other two sampling locations. When solenoid switch A closed to switches B1, B2, and B3, the monitor purged from the fresh air source. When switch A opened, the monitor sampled sequentially from the three
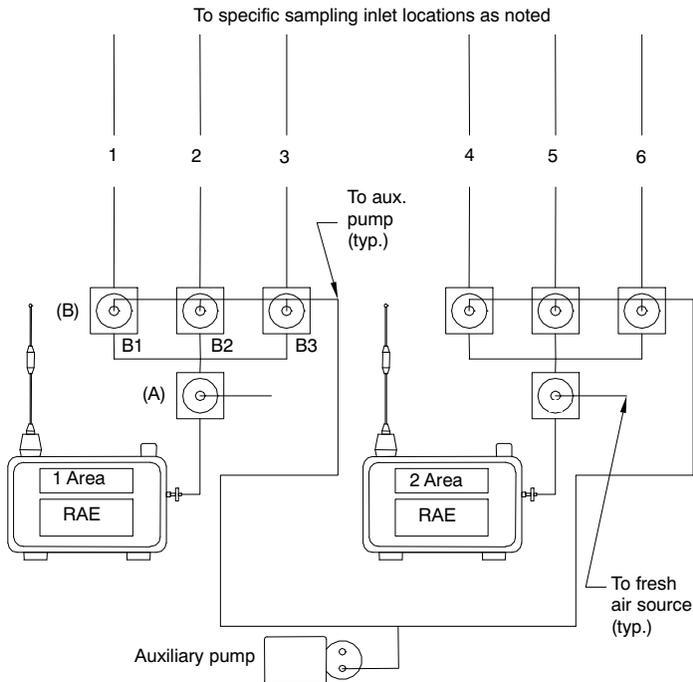

Figure 5. Gas monitoring control system.

sampling locations. Solenoid switch A closed momentarily to draw fresh air into the monitor when switching between the three sensor inlet locations. This cycle helped to prevent residual gas from the previous location from influencing the reading from the current location. The time interval between sampling locations was 1 s.

The gas concentrations within the confined airspace were monitored continuously at 1 s intervals until the concentration level stabilized during agitation and then during ventilation. The five grids (G1 to G5 in fig. 4) recorded real-time measurements at the upper and lower levels. One monitor measured gas concentrations at the upper level, while the second monitor measured gas concentrations at the lower level. Thus, six gas sensor inlets could be monitored during real-time testing, limiting the initial tests to one grid at a time (fig. 4). The gas concentration distribution within the entire airspace was obtained by sequentially monitoring the five grids, which required a total of five tests. The five tests performed to obtain the gas concentration distribution of the entire tank were treated as one replication for a ventilation strategy. The same procedure for five grids was repeated three times sequentially. This sequence minimized time, temperature differences, and manure aging between replications.

Ventilation System

A two-speed Dayton 4TM84 fan with published capacities of 1.75×10^5 L min^{-1} (2.92 m^3 s^{-1}, high capacity) and 1.14×10^5 L min^{-1} (1.9 m^3 s^{-1}, low capacity) at an operating static pressure of 0 Pa ventilated the confined space. Experiments conducted in accordance with AMCA Standard 203-90 (AMCA, 1987) developed fan capacity curves. Two Dwyer inclined water manometers (resolution = 0.5 mm water) were used to measure the static pressure and velocity pressure. The corresponding calculated airflow rates for the high-capacity and low-capacity speeds were 2.67 and 1.53 m^3 s^{-1}, respectively, based on the on-site measurements of static pressure and the developed fan capacity curves. Thus, the air exchange (AC) rates in the confined space corresponding to high-capacity and low-capacity operation were 5 and 3 AC min^{-1}, respectively.

Placed on top of the plank decking, the two-speed Dayton fan rested over 0.61 m $\times$ 0.61 m openings cut into the decking (fig. 6) and provided air exchange in the rectangular confined-space manure tank. The fresh air supplied for the forced-air ventilation through the fan was directly above the fan intake. This fan setup simulated a likely configuration in a real farm setting. This configuration would yield, at worst, conservative reduction times for the toxic gases due to the potential for some contaminated air re-entering the
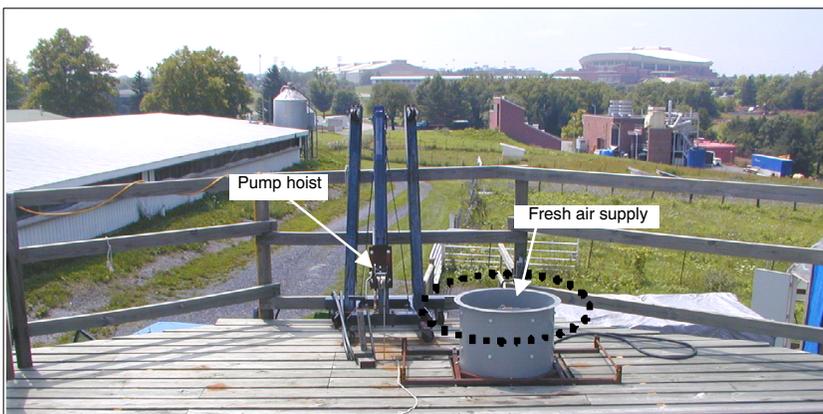

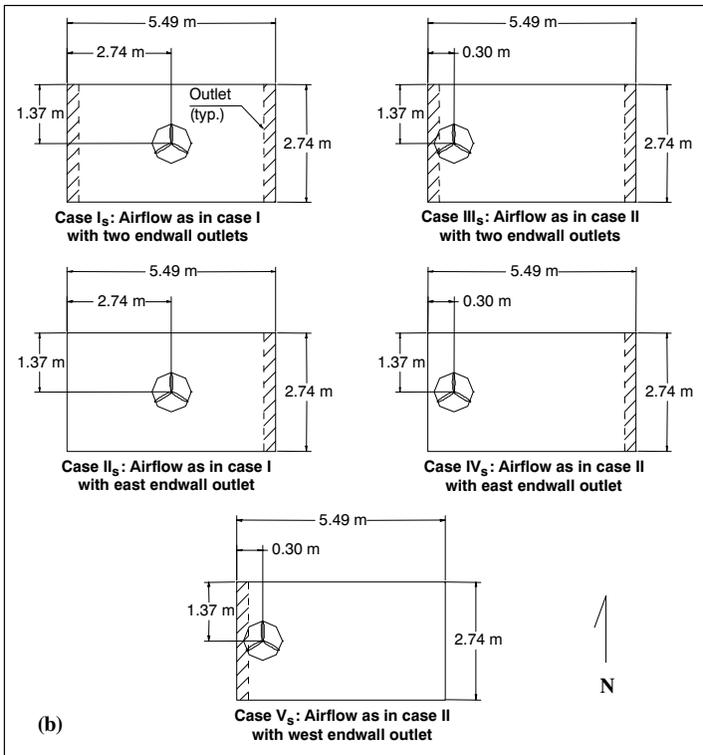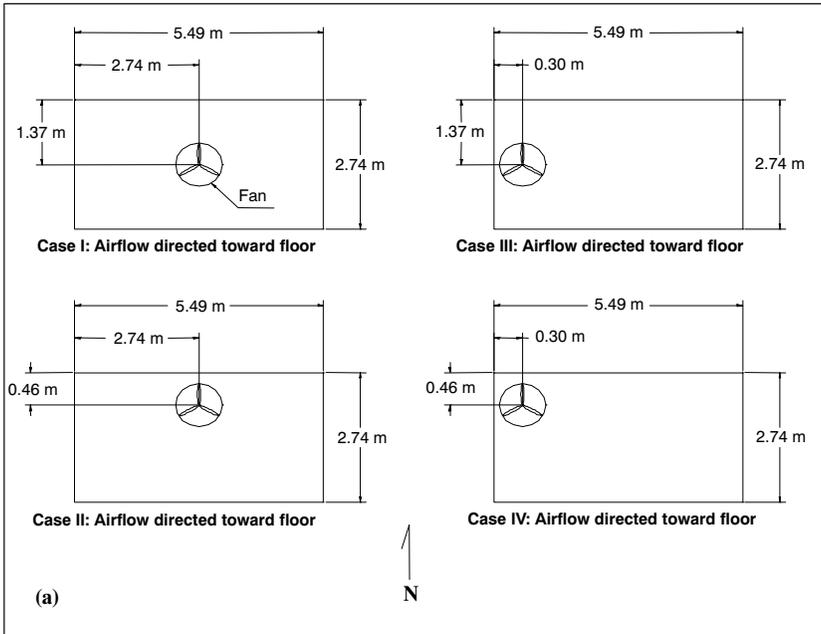**Figure 6. Fan placement on slotted cover decking.**

Figure 7. Schematic of candidate ventilation configurations for (a) fully slotted and partially slotted cover types and (b) solid cover type.

rectangular manure tank through the fan intake during ventilation. A fresh air source with zero noxious gas concentration would yield shorter contaminant gas evacuation times.

Candidate Ventilation Strategies

Varying fan location, outlet location, and air exchange rate (high = 5 AC min⁻¹, low = 3 AC min⁻¹) generated several candidate ventilation strategies for each cover type. Figure 7 illustrates the candidate ventilation configurations identified for the fully slotted and partially slotted cover types (fig. 7a) and the solid cover type (fig. 7b). The orientations of the covers in figure 7 are consistent with the orientation shown in figure 2. Only two fan locations, each along the storage centerline, were selected for the solid cover case. For the solid cover system (fig. 7b), air was exhausted through one or both the 2.13 m long by 0.13 m high outlets located at the top of the end walls of the confined-space manure tank. The end wall outlets remained closed for the fully slotted and partially slotted cover test cases (fig. 7a). The cover slots served as the outlets for the fully slotted and partially slotted cover test cases.

Experimental Schedule

The efforts of this research consisted of two data collection phases. Phase I data collection was used to determine whether the gas sensing locations within a grid across the width of the rectangular manure tank could be represented using a single, central location in order to simplify testing methods for the second phase of data collection (phase II). The second phase of data collection efforts focused on the monitoring of gas concentrations only at the centermost sampling locations for each grid, based on phase I results, except for partially slotted cover cases III and IV (fig. 7a). In the second phase, the best ventilation strategy for each cover type was identified. Table 1 lists the experimental schedules for phases I and II. The tests considered the three cover treatment types, the two air exchange rates, and the fan location as independent variables. The fan location varied per cover treatment type, as shown in figure 7. Only a selected set of air exchange rates and fan locations were selected for phase 1 testing. Phase II experi–

Table 1. Experimental schedules for phases I and II.

Phase	Cover Type	AC Rate[a] (AC min⁻¹)	Ventilation Strategy[b]	Sampling Location	Replications
	Fully slotted	3 and 5	Cases I to IV	Five grids, three locations[c]	3
I	Partially slotted	5	Cases II and IV	Five grids, three locations[c]	1
	Solid	5	Case I	Five grids, three locations[c]	1
	Fully slotted	3 and 5	Cases I to IV	Five grids at center line	3
II	Partially slotted	3 and 5	Cases I to IV	Five grids at center line	3
	Solid	3 and 5	Cases I to V	Five grids at center line	3

[a] Air exchange rates: high = 5 AC min⁻¹, low = 3 AC min⁻¹.
[b] See figure 7.
[c] See figure 4.

mentation considered each combination of the two air exchange rates (i.e., 3 and 5 AC min^{-1}) and candidate fan and outlet locations for each cover type.

Preliminary Tests (Phase I)

Phase I experimental protocols determined the significance of the differences in gas evacuation data from sampling inlet locations at each grid across the width of the tank (e.g., locations 1 to 3 of each grid in fig. 4). The experimental protocols for phase II research efforts were greatly simplified by collecting data at only location 2 of each grid (fig. 4) if the differences between locations were not significant.

Data Analysis Method

The criteria for assessing ventilation effectiveness in this research were the time required to reach a hydrogen sulfide concentration level of 10 ppm (T_{pel}) and the time required to achieve a hydrogen sulfide concentration to 25% of the initial concentration (C_0) at the beginning of ventilation (T_{25}). The T_{pel} value characterizes the time taken for peak, stabilized gas concentrations to decrease to the OSHA permissible exposure limits (PEL) immediately following the cessation of agitation and the commencement of ventilation. The T_{25} value represents similarity and uniformity in gas concentration decrease between each sampling inlet location with different initial concentrations.

Phase I data analysis utilized an ANOVA general linear model (eq. 1) (Minitab, 2005) to perform statistical analysis to determine the difference between the T_{pel} values of each location in a grid (fig. 4) for each cover type:

$$y_{ij} = \alpha_i + \beta_j + (\alpha\beta)_{ij} \qquad (1)$$

where

y_{ij} = response variable (T_{pel})
α_i = grid factor (grids 1 through 5)
β_j = location factor (locations 1 through 3)
$(\alpha\beta)_{ij}$ = grid and location combination factor to test strength between grid and location.

The null hypothesis tested with this model states that the three locations within each grid may be pooled across the width of the rectangular manure storage to a single, central location. A p-value greater than α = 0.05 for the main factor effect (term β_j of eq. 1) suggests that the three locations within each grid across the width of the rectangular manure tank can be represented by a single central location at a 95% confidence level. The tested model represented all fan location cases, both high and low air exchange rates, and all upper and lower sampling inlet locations per grid.

Phase I Results

Typical H$_2$S Concentration Reduction Curve During Forced Ventilation

Figure 8 shows a typical normalized H$_2$S concentration reduction curve during forced-air ventilation for location 1 at grid 3 (fig. 4) at the upper level at the high air exchange rate for the fully slotted cover case. Because initial gas concentrations were different between sampling locations and test runs, the gas concentrations were normalized to the initial concentration at each sampling location (the measured gas concentration at the sampling location at each time was divided by the initial concentration at the sampling location). The concentration reduction curves for other sampling locations and for other test cases showed a similar trend. In figure 8, time zero ($t = 0$ s) represents the point at which agitation ceased and ventilation commenced.
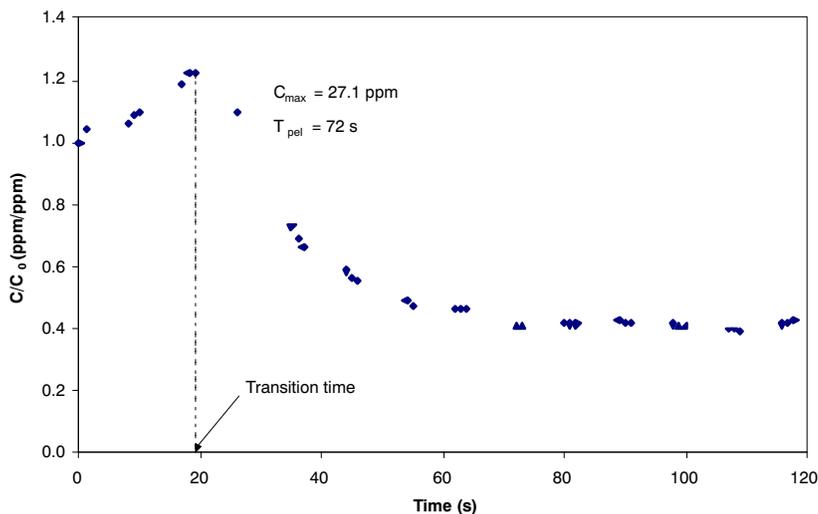
Figure 8. H$_2$S reduction for the fully slotted cover system at the high air exchange rate (case I, grid 3, upper level).

A period of gas concentration instability occurred immediately after manure agitation ceased and after ventilation commenced (fig. 8: from t = 0 s to t ≈ 20 s). This unstable period signified a transition time between the commencement of ventilation and the beginning of gas concentration reduction. This unstable period existed because when agitation ceased, the manure surface did not immediately become calm. Furthermore, air from the fan began to agitate the manure surface. The transition time is the time required for these two highly transient characteristics to stabilize. All sampling locations for all tests portrayed this characteristic. In figure 8, the actual gas concentration reduction process began 20 s after agitation ceased and ventilation commenced. Considering the existence of this unstable period, the reported T_{pel} and T_{25} values were all measured from the beginning of ventilation (transition time included).

Figure 9 shows the corresponding non-linear semi-log gas concentration reduction plot (ln(C/C$_0$) vs. t). The measurements of time started from the end of the transition period in this plot. The reduction trend generated shows that a quadratic regression equation strongly fit the gas reduction plot, with an R^2 value of 95.6%. Semi-log gas reduction plots of all other sampling locations for all phase I tests showed similar tendencies, with R^2 values ranging from 90% to 99% (Pesce, 2005). Phase II gas concentration reduction plots were similar for all locations and tests, with R^2 values from 90% to 99% (Pesce, 2005). The non-linearity of the reduction curve in semi-log space suggests that H$_2$S emissions from the manure surface and/or recirculation of some contaminant air between air outlets and air inlets influenced the gas reduction response (Albright, 1990).

Using a Single Representative Sampling Location

Tables 2 and 3 list the p-values obtained from the ANOVA analysis for T_{pel} values for all fully slotted, partially slotted, and solid cover test cases for H$_2$S in phase I. All p-values were greater than 0.05 for the fully slotted cover test cases, showing no significant differences between sampling locations within a grid for both the upper and lower levels at both the high and low air exchange rates. This demonstrated the suitability of using the central sampling location to represent gas concentration levels across the width of the
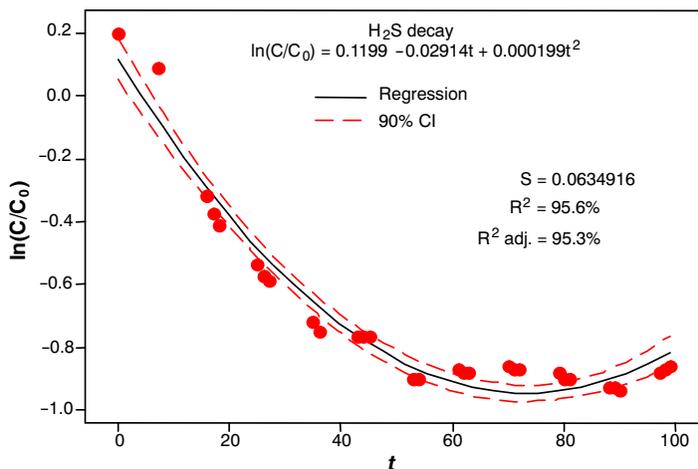
Figure 9. Semi-log plot of H$_2$S reduction for the fully slotted cover case (case I, grid 3, upper level, high air exchange rate).

Table 2. P-values for the location main effect from Minitab ANOVA analysis for T$_{pel}$ for the fully slotted and partially slotted cover tests.

Cover Type	Case I[a]		Case II		Case III		Case IV	
	High[b]	Low[b]	High	Low	High	Low	High	Low
Fully slotted	0.990	0.995	0.580	0.830	0.653	0.846	0.995	0.970
Partially slotted	N/A	N/A	0.745	N/A	N/A	N/A	0.339	N/A

[a] Ventilation strategies defined in figure 7a.
[b] Air exchange rate: high = 5 AC min^{-1}, low = 3 AC min^{-1}.

Table 3. P-value for the location main effect from Minitab ANOVA analysis for T$_{pel}$ the solid cover tests.

Cover Type	Case I[a], High AC rate[b]
Solid cover	p-value = 0.920

[a] Ventilation strategy defined in figure 7b.
[b] High = 5 AC min-1.

rectangular manure tank within a grid at the high and low air exchange rates (fig. 4). Similar results were observed for all partially slotted cover cases tested, indicating that the central sampling location is representative of gas concentrations across the tank width. However, the decision was made to monitor all three locations within a grid for all partially slotted cover cases in phase II, since the p-values were considerably lower than those for the fully slotted cover cases and since the partially slotted cover configuration lacked symmetry in boundary conditions. Phase I measurements were conducted only for case I at the high air exchange rate for the solid cover case. The p-value (0.92) for the solid cover case tested was larger than 0.05, similar to the p-values for the fully slotted cover cases, thereby showing no significant differences between sampling locations within a grid for both the upper and lower levels at the high air exchange rate. Thus, the central sampling location was identified as being representative of gas concentrations across the width of the confined space within each grid of the solid cover case in phase II.

Screening Candidate Ventilation Strategies (Phase II)

The collection of gas concentration data occurred only at location 2 of each grid and level for all the solid and fully slotted cover cases in phase II based on phase I results. The collection of gas concentration data for the partially slotted cover type took place across all locations at each grid and level for all ventilation cases. Hydrogen sulfide concentration reduction during forced-air ventilation was measured for all ventilation strategy cases for the three cover types shown in figure 7. Table 4 lists the maximum measured H_2S initial concentration values at location 2 of grid 1 (fig. 4) for four ventilation cases (fig. 7a) for the fully slotted cover type. The initial concentration for each ventilation case was not the same. Similarly, the initial concentrations were different across all ventilation cases for the partially slotted and the solid cover types. To eliminate this variable from the comparisons of ventilation effectiveness, the measured gas concentrations at a given time after ventilation commenced were normalized to the initial concentration by the ratio of C/C_0, where C is the concentration at a given time, and C_0 is the initial concentration. The effectiveness of the ventilation strategies for reducing gas concentrations was then evaluated by comparing the time required to reduce H_2S concentrations to 0.25 of the initial concentration (T_{25}).

An ANOVA analysis for all T_{25} values determined if each ventilation strategy significantly affected the H_2S concentration reduction in the confined airspace. Significant differences identified by ventilation strategy factors led to the comparison of mean T_{25} values for the entire confined airspace to identify the best of the candidate ventilation strategies for each cover type. Mean T_{pel} and $T_{pel-max}$ values were used to corroborate and strengthen the conclusions based on T_{25} results.

Phase II Results and Discussions

Tables A1 to A3 in the Appendix list the mean T_{25} values from three replicated tests across the entire confined airspace at each grid. Data are presented for the upper and lower levels (fig. 4) for all the ventilation strategies for the fully slotted (table A1), partially slotted (table A2), and solid cover cases (table A3) at the high (5 AC min^{-1}) and low (3 AC min^{-1}) air exchange rates.

Statistical ANOVA Analysis

An ANOVA statistical analysis of the reduction time (T_{25}) was conducted to identify significant difference in the T_{25} values between each predictor variable of ventilation strategy, grid, sampling location level, air exchange rate, and their corresponding interactions. The null hypothesis stated that there is no significant difference in the T_{25} values between each predictor variable.

Table 5 lists the p-values returned from the Minitab ANOVA analysis of all measured T_{25} values for all the three cover types (fully slotted, partially slotted, and solid). All p-values were less than the 0.05 alpha level for the fully slotted cover cases except for those of the predictor variables of air exchange rate and level by air exchange rate

Table 4. Initial concentrations for case I to case IV for the fully slotted cover type at location 2 at grid 1 (upper level, high air exchange rate).

Cover Type	Location 2, Grid 1 (upper level, high air exchange rate)	
	Ventilation Case	C_0 (ppm)
Fully slotted	I	141.0
cover	II	131.0
	III	121.0
	IV	130.0

interaction. These results indicate that the air exchange rate and the level by air exchange rate interaction were not statistically significant influencing factors on gas evacuation time (T_{25}). Thus, the differences between all predictor variables except for the air exchange rate and the level by air exchange rate interaction were statistically significant ($p < 0.05$) factors. Therefore, the measured T_{25} values between ventilation strategies, grids, and levels were all significantly different for the fully slotted cover cases.

T_{25} values were measured at three sampling locations within a grid (fig. 4) with sampling location as a predictor variable because the partially slotted cover configuration lacked boundary condition symmetry. All p-values were less than 0.05 for the partially slotted cover cases except for those of predictor variables of sampling location, ventilation strategy by air exchange rate interaction, sampling location by air exchange rate interaction, sampling location by level interaction, grid by sampling location interaction, and level by air exchange rate interaction. The non-significance of the sampling location predictor and all sampling location interactions further supports the phase I results, i.e., the central sampling location satisfactorily represented gas concentration levels across the width within one grid at the same level for all the partially slotted ventilation cases. The results also indicate that the observed differences in mean T_{25} values between ventilation cases, air exchange rates, grids, and levels are significant ($p < 0.05$). Thus, the ventilation strategy, the air exchange rate, the grid, and the level significantly ($p < 0.05$) influenced T_{25}.

For the solid cover cases, p-values were greater than 0.05 for the interactions of ventilation strategy by grid, grid by level, and grid by air exchange rate. This resulted in the acceptance of the null hypothesis for these predictor variables (ventilation strategy and grid) and their corresponding interactions and the rejection of the null hypothesis for all other predictor variables. These results indicate that the ventilation strategies, the grids, and the levels significantly ($p < 0.05$) influenced T_{25}.

Table 5. P-values[a] from ANOVA analysis for all T_{25} values for H_2S for the three cover cases.

Source[b]	H_2S - T_{25}[c]		
	Fully Slotted Cover	Partially Slotted Cover	Solid Cover
Ventilation strategy	0.000	0.000	0.000
Grid	0.000	0.000	0.000
Level	0.000	0.000	0.000
Air exchange rate	0.958*	0.000	0.000
Ventilation strategy × grid	0.000	0.000	0.609*
Ventilation strategy × level	0.000	0.000	0.000
Ventilation strategy × air exchange rate	0.000	0.292*	0.000
Grid × level	0.036	0.013	0.867*
Grid × air exchange rate	0.000	0.012	0.779*
Level × air exchange rate	0.086*	0.341*	0.046
Sampling location	N/A	0.839*	N/A
Sampling location × level	N/A	0.946*	N/A
Sampling location × air exchange rate	N/A	0.512*	N/A
Grid × sampling location	N/A	0.816*	N/A

[a] Differences between predictor variables were statistically significant when p < 0.05.
[b] All sources were treated as predictor variables for the Minitab ANOVA general linear model analysis.
[c] * = not statistically significant at p ≤ 0.05.

Screening the Best Ventilation Strategies Using Mean T_{25}

Figures 10 and 11 show the mean T_{25} values with standard error bars for all the candidate ventilation strategies (cases I to IV) for the fully slotted cover case. Based on the comparisons of T_{25} values in figures 10 and 11, case I was the most effective of the candidate ventilation strategies at the high and low air exchange rates. The lower level T_{25} values were most often higher than those of the upper level for H_2S, as expected due to its high density compared to air.

Figures 12 and 13 show the mean T_{25} values across the entire confined airspace at the upper and lower levels for all the candidate ventilation strategies of the partially slotted cover type at the high and low air exchange rates (high = 5 AC min^{-1}, low = 3 AC min^{-1}), respectively. Figure 12 shows similar T_{25} values for case I and case III ventilation strategies at the high air exchange rate for both the upper and lower levels. The mean T_{25} for case IV at the lower level was highest, even though case IV had the lowest T_{25} value at the high air exchange rate at the upper level. Case I was the most effective of the
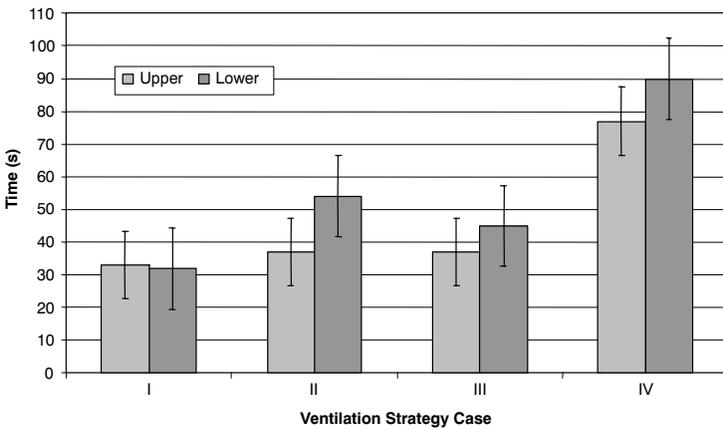

Figure 10. Mean T_{25} values for H_2S for each fully slotted cover ventilation strategy case at the high air exchange rate.
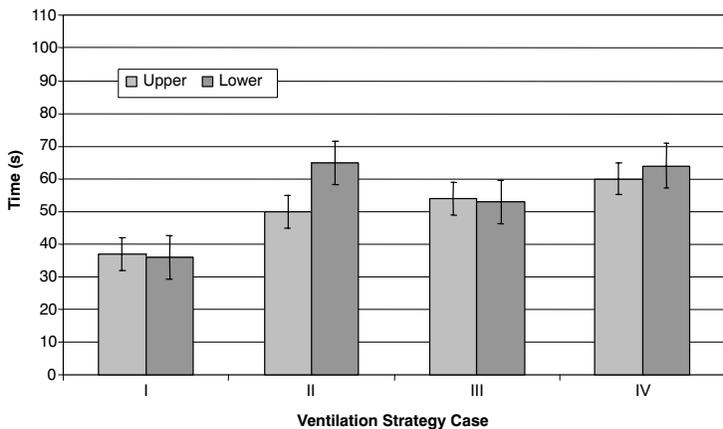

Figure 11. Mean T_{25} values for H_2S for each fully slotted cover ventilation strategy case at the low air exchange rate.

candidate ventilation strategies at the high air exchange rate since it had lower T_{25} at the lower level. Figure 13 shows that case I had the lowest T_{25} values at both the upper and lower levels at the low air exchange rate. The lower level T_{25} values were most often higher than those of the upper level for H_2S gas reduction trend, as expected. This held true for all ventilation strategy cases, except case I at the low air exchange rate. Although not considered and controlled, this exception most likely occurred due to the recirculation of contaminated air into the upper level of the airspace through the slots and the fan intake due to undefined wind conditions on the test dates.

Figures 14 and 15 show the mean T_{25} values at the upper and lower levels for all the candidate ventilation strategies of the solid cover case at the high and low air exchange rates (high = 5 AC min^{-1}, low = 3 AC min^{-1}), respectively. Figures 14 and 15 show that ventilation strategy case III returned the lowest T_{25} values for the lower levels at the high and low air exchange rates. Case I had the highest T_{25} value at the lower level at the high air exchange rate, even though it had the lowest T_{25} value at the upper level at the low
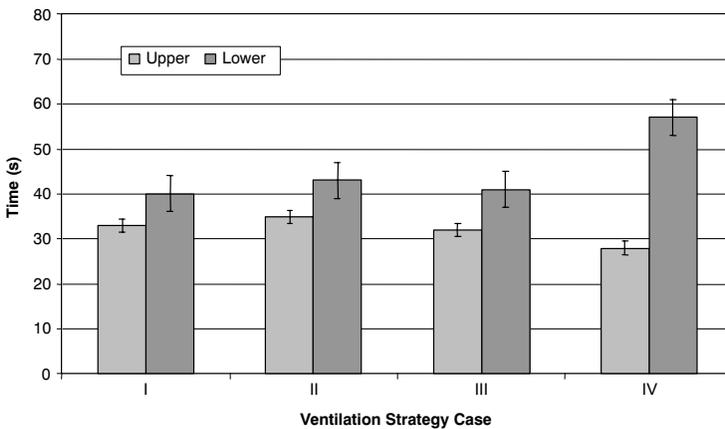

Figure 12. Mean T_{25} values for H_2S for each partially slotted cover ventilation strategy case at the high air exchange rate.
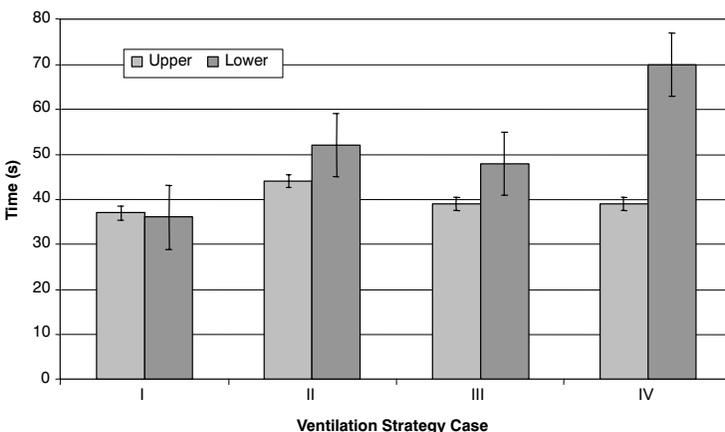

Figure 13. Mean T_{25} values for H_2S for each partially slotted cover ventilation strategy case at the low air exchange rate.

air exchange rate. Thus, case III was the most effective of the candidate ventilation strategies at the high and low air exchange rates for the solid cover case.

Screening the Best Ventilation Strategies Using Mean T_{pel} and $T_{pel\text{-}max}$

Fully Slotted Cover Cases

Figures 16 and 17, respectively, show the mean T_{pel} values at the high and low air exchange rates, across the entire airspace for all the candidate ventilation strategies (cases I to IV) for the fully slotted cover type. Figure 16 shows similar T_{pel} values for case I and case III ventilation strategies at the high air exchange rate for the upper level sampling inlet location. However, the case I lower level reduction to the OSHA PEL of 10 ppm was more rapid than that of case III. Furthermore, as shown in figure 17, the case I ventilation strategy returned the lowest T_{pel} values for H_2S at the low air exchange rate for both the upper and lower levels. The T_{pel} trends corroborate the selection of case I as the most effective of the candidate ventilation strategies at the high and low air exchange rates for reducing H_2S concentrations to the OSHA PEL of 10 ppm for storages with fully

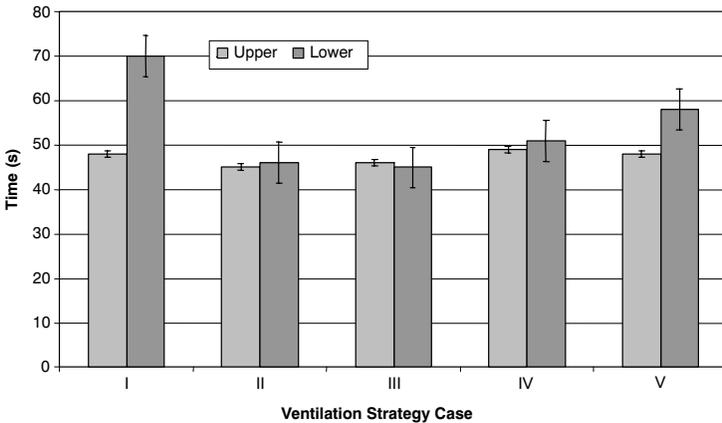**Figure 14. Mean T_{25} values for H_2S for each solid cover ventilation strategy case at the high air exchange rate.**
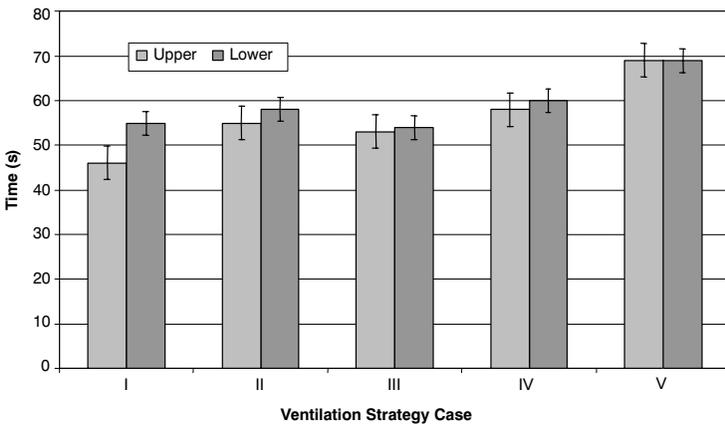

Figure 15. Mean T_{25} values for H_2S for each solid cover ventilation strategy case at the low air exchange rate.

slotted covers. The lower level T_{pel} values were most often higher than those of the upper level for the H_2S gas reduction trend, as expected. This held true for all ventilation cases, except case I at the high and low air exchange rates. Although not considered and controlled, this exception most likely occurred due to the recirculation of contaminated air into the upper level of the airspace through the slots and the fan intake due to undefined wind conditions on the test dates.

Table 6 lists the $T_{pel-max}$ (maximum time to reduce H_2S concentration to OSHA PEL anywhere in the confined-space manure storage for the given ventilation strategy) for H_2S concentrations at grids 1 to 5 at the high and low air exchange rates for case I through IV ventilation strategies for the fully slotted cover type. The values in table 6 are $T_{pel-max}$ values of three replicated tests for each sampling location. The $T_{pel-max}$ values for ventilation strategies I, II, III, and IV were 57, 99, 100, and 234 s, respectively. Ventilation case I also had the lowest mean T_{25} (table 5) for the entire confined-space manure storage. The $T_{pel-max}$ trends further corroborate the superior ability of ventilation strategy case I to evacuate H_2S from the confined-space manure tank with a fully slotted cover.
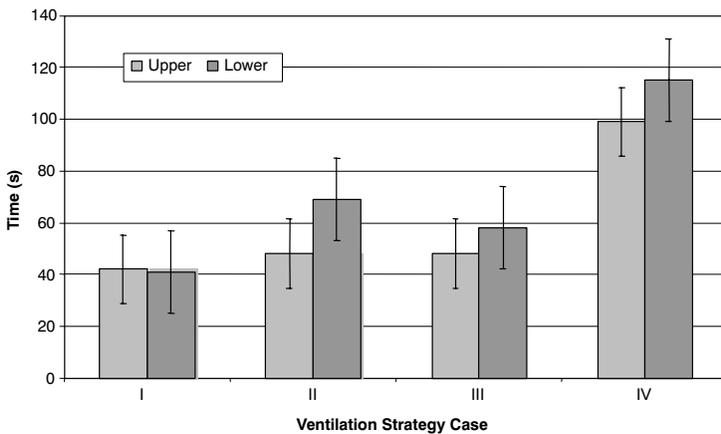

Figure 16. Mean T_{pel} values for H_2S for each fully slotted cover ventilation strategy case at the high air exchange rate.
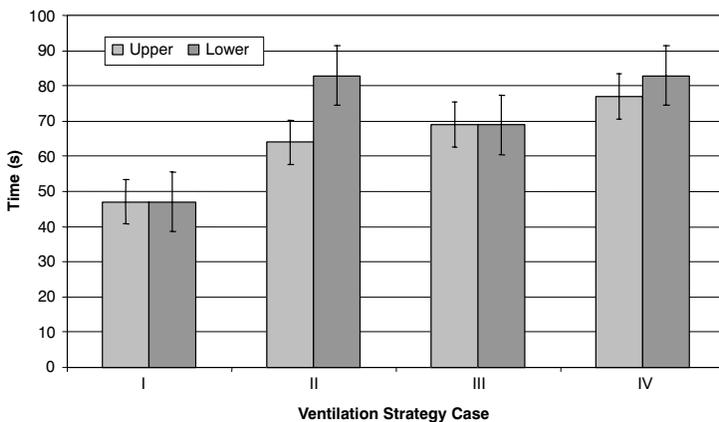

Figure 17. Mean T_{pel} values for H_2S for each fully slotted cover ventilation strategy case at the low air exchange rate.

Table 6. $T_{pel-max}$ values (s) for H_2S reduction for the fully slotted cover cases.
Values in parentheses represent the maximum initial concentration (ppm).

Case[a]	AC Rate[b]	Grid and Level[c]									
		1		2		3		4		5	
		U	L	U	L	U	L	U	L	U	L
I	High	4 (141)	45 (161)	45 (141)	44 (161)	34 (141)	35 (161)	42 (141)	38 (161)	56 (141)	57 (161)
	Low	47 (141)	45 (161)	52 (141)	55 (161)	54 (141)	53 (161)	53 (141)	52 (161)	37 (141)	38 (161)
II	High	52 (131)	65 (133)	45 (131)	63 (133)	46 (131)	81 (133)	54 (131)	72 (133)	54 (131)	75 (133)
	Low	72 (128)	88 (126)	62 (128)	81 (126)	72 (128)	99 (126)	63 (128)	82 (126)	70 (128)	83 (126)
III	High	45 (121)	81 (114)	48 (121)	97 (112)	45 (121)	64 (112)	47 (117)	100 (107)	37 (116)	97 (107)
	Low	63 (130)	98 (126)	62 (130)	83 (126)	63 (130)	90 (126)	54 (130)	82 (126)	63 (130)	98 (126)
IV	High	72 (130)	72 (130)	81 (130)	99 (130)	90 (130)	89 (130)	99 (130)	98 (130)	162 (130)	234 (130)
	Low	74 (126)	81 (126)	82 (126)	72 (126)	73 (126)	72 (126)	90 (126)	97 (126)	81 (126)	99 (126)

[a] Ventilation strategies defined in figure 7a.
[b] Air exchange rate: high = 5 AC min^{-1}, low = 3 AC min^{-1}.
[c] Grid and level are defined in figure 4 (U = upper, L = lower).

Partially Slotted Cover Cases

Figures 18 and 19, respectively, show the mean T_{pel} values across the entire confined airspace at the upper and lower levels for all the candidate ventilation strategies of the partially slotted cover case at the high and the low air exchange rates (high = 5 AC min^{-1}, low = 3 AC min^{-1}), respectively. Figure 18 shows similar T_{pel} values for case I, II, and III ventilation strategies at the high air exchange rate for both the upper and the lower levels. Figure 19 presents similar performances between cases I, II, and III at the low air exchange rate for both the upper and the lower level sampling locations. Case I was slightly better at the upper level at the high air exchange rate, and case III was slightly better at the low air exchange rate at the lower level based on the comparisons in figures 12 and 13. The T_{pel} trends corroborate that cases I and III were the most effective of the candidate ventilation strategies at the high and low air exchange rates, respectively, for storage facilities with the partially slotted cover type.

Table 7 lists the measured $T_{pel-max}$ values for H_2S at grids 1 to 5 at the high and low air exchange rates for case I through IV ventilation strategies for the partially slotted cover type. The $T_{pel-max}$ values for ventilation strategies I, II, III, and IV were 79, 92, 79, and 116 s, respectively. Ventilation cases I and III also had the lowest mean T_{25} and T_{pel} values for H_2S removal throughout the entire confined-space manure tank at the high and low air exchange rates. The $T_{pel-max}$ trends further corroborate the superior ability of ventilation strategy cases I and III to remove H_2S from the confined-space manure tank with a partially slotted cover.

Solid Cover Cases

Figures 20 and 21, respectively, show the mean T_{pel} values at the upper and lower levels for all the candidate ventilation strategies of the solid cover cases at the high and low air exchange rates (high = 5 AC min^{-1}, low = 3 AC min^{-1}). Figures 20 and 21 show

that ventilation strategy case III returned the lowest T_{pel} values for both the upper and lower levels at the high and low air exchange rates. This trend corroborates the selection of case III as the most effective of candidate ventilation strategies at the high and low air exchange rates for the solid cover type. The lower level T_{pel} values were most often higher than those of the upper level for the H_2S gas concentration reduction trend, as expected. This held true for all ventilation cases, except case V at the low air exchange rate. This exception most likely occurred due to air entrapment of the heavy H_2S gas beneath the solid cover surface at the upper level sampling location.

Table 8 lists the $T_{pel-max}$ values for H_2S at grids 1 to 5 at the high and low air exchange rates for case I through V ventilation strategies for the solid cover type. The values in table 8 are the $T_{pel-max}$ values of three replicated tests for each sampling location. The $T_{pel-max}$ values for ventilation strategies I, II, III, IV, and V were 136, 136, 100, 128, and 153 s, respectively. Case III also had the lowest mean T_{25} and T_{pel} values for H_2S removal throughout the entire confined-space manure tank. The $T_{pel-max}$ trends further corroborate the superior ability of the case III ventilation strategy to remove H_2S from the confined-space manure tank with a solid cover.
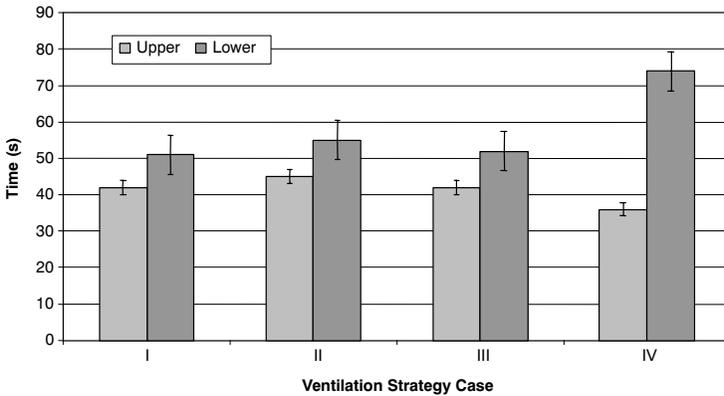

Figure 18. Mean T_{pel} values for H_2S for each partially slotted cover ventilation strategy case at the high air exchange rate.
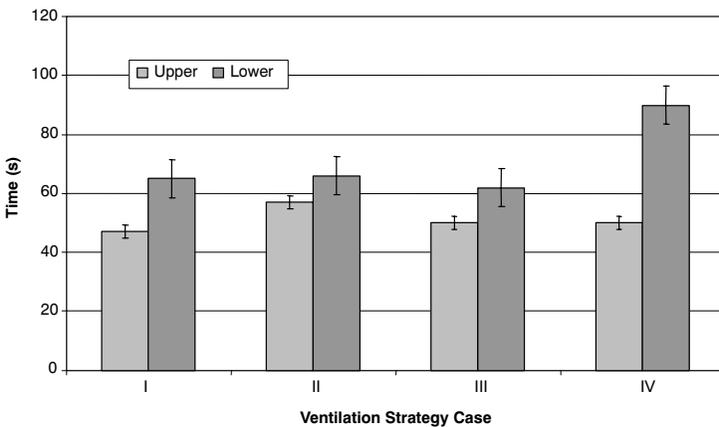

Figure 19. Mean T_{pel} values for H_2S for each partially slotted cover strategy case at the low air exchange rate.

Table 7. $T_{pel-max}$ values (s) for H_2S reduction for the partially slotted cover cases.
Values in parentheses represent the maximum initial concentration (ppm).

Case[a]	AC Rate[b]	Grid and Level[c]									
		1		2		3		4		5	
		U	L	U	L	U	L	U	L	U	L
I	High	43 (83)	54 (108)	37 (83)	46 (108)	36 (82)	45 (108)	44 (50)	55 (108)	52 (47)	65 (104)
	Low	53 (63)	66 (72)	54 (65)	68 (70)	47 (64)	59 (72)	61 (51)	76 (88)	63 (53)	79 (88)
II	High	56 (50)	61 (39)	43 (35)	45 (44)	36 (37)	37 (43)	62 (34)	83 (46)	47 (44)	81 (39)
	Low	55 (32)	56 (28)	37 (35)	45 (39)	74 (33)	80 (49)	63 (46)	92 (36)	72 (37)	97 (35)
III	High	46 (57)	58 (67)	46 (55)	58 (66)	43 (52)	54 (66)	46 (59)	58 (67)	53 (60)	66 (63)
	Low	45 (63)	56 (64)	53 (62)	66 (63)	45 (63)	56 (64)	63 (68)	79 (70)	63 (66)	79 (68)
IV	High	27 (73)	63 (75)	44 (50)	81 (66)	45 (64)	92 (79)	47 (57)	100 (78)	45 (64)	97 (84)
	Low	45 (68)	90 (66)	54 (56)	99 (71)	54 (57)	116 (81)	63 (67)	98 (80)	63 (62)	98 (94)

[a] Ventilation strategies defined in figure 7a.
[b] Air exchange rate: high = 5 AC min-1, low = 3 AC min-1.
[c] Grid and level are defined in figure 4 (U = upper, L = lower).
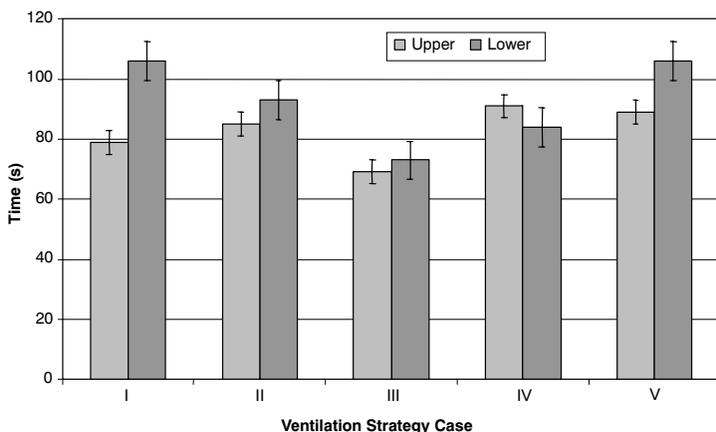
Figure 20. Mean T_{pel} values for H_2S for each solid cover ventilation strategy case at the high air exchange rate.

The mean T_{25}, mean T_{pel}, and $T_{pel-max}$ for H_2S removal from the confined-space manure tank of this research were used to identify the best from a candidate list of ventilation strategies for each of the three cover types. The ranking of the candidate ventilation strategies for each cover case was the same for each evacuation time criterion: (1) ventilation case I (fig. 7a) was the best for the confined-space manure tank with the fully slotted cover type for both the high and the low air exchange rates; (2) ventilation cases I and III (fig. 7a) were the best for the confined-space manure tank with the partially
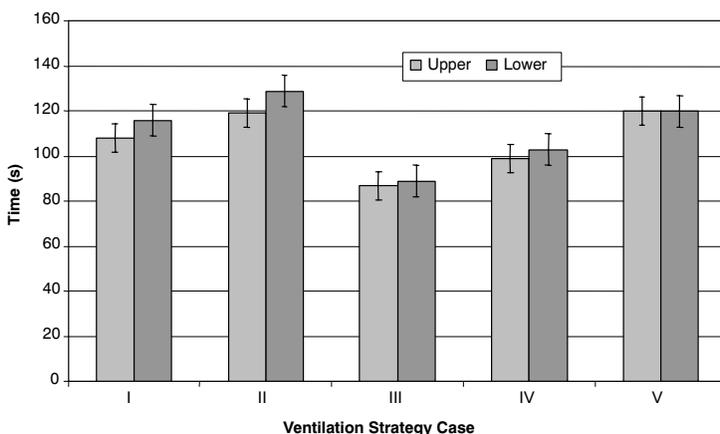
Figure 21. Mean T_{pel} values for H_2S for each solid cover ventilation strategy case at the low air exchange rate.

Table 8. $T_{pel-max}$ values (s) for H_2S reduction for the solid cover cases.
Values in parentheses represent the maximum initial concentration (ppm).

		Grid and Level[c]									
		1		2		3		4		5	
Case[a]	AC Rate[b]	U	L	U	L	U	L	U	L	U	L
I	High	91 (155)	126 (155)	90 (155)	117 (155)	97 (155)	124 (155)	99 (155)	135 (155)	98 (155)	136 (155)
	Low	117 (166)	117 (114)	116 (166)	117 (111)	117 (166)	117 (111)	119 (166)	135 (126)	121 (126)	126 (120)
II	High	82 (155)	90 (155)	82 (155)	87 (155)	89 (155)	91 (155)	100 (155)	108 (155)	90 (155)	108 (155)
	Low	127 (177)	136 (177)	119 (177)	128 (177)	126 (177)	134 (177)	127 (177)	136 (177)	135 (177)	135 (177)
III	High	72 (144)	72 (140)	65 (144)	72 (140)	70 (144)	71 (140)	81 (144)	89 (140)	81 (144)	81 (140)
	Low	89 (146)	89 (139)	82 (139)	90 (139)	89 (139)	90 (139)	99 (139)	99 (139)	99 (139)	100 (139)
IV	High	99 (133)	90 (125)	99 (134)	89 (124)	99 (134)	90 (124)	83 (128)	90 (117)	89 (128)	81 (117)
	Low	108 (143)	108 (138)	108 (143)	100 (129)	100 (143)	107 (143)	116 (143)	128 (143)	117 (143)	126 (143)
V	High	100 (143)	118 (138)	99 (143)	117 (138)	98 (143)	124 (138)	109 (143)	117 (138)	108 (143)	125 (138)
	Low	117 (143)	118 (139)	116 (143)	124 (139)	117 (143)	117 (138)	153 (143)	135 (139)	146 (143)	134 (139)

[a] Ventilation strategies defined in figure 7a.
[b] Air exchange rate: high = 5 AC min-1, low = 3 AC min-1.
[c] Grid and level are defined in figure 4 (U = upper, L = lower).

slotted cover type for the high and low air exchange rates, respectively; and (3) ventilation case IV (fig. 7b) was the best for the confined-space manure tank with the solid cover for both the high and low air exchange rates.

Additionally, a database of H_2S concentration reduction versus ventilation time during forced-air ventilation was developed for the best ventilation strategy of each cover type identified in phase II of the research. The database included the H_2S concentration reduction versus time during forced ventilation at all sampling locations along the longitudinal centerline of the tank for five grids at both the upper and lower levels. This database is published and available in Pesce (2005). This database can be used to validate computational fluid dynamics (CFD) modeling protocols for simulation of ventilation strategies for removal of contaminant gases from on-farm confined-space manure storage facilities.

Conclusions

The results of this research identify, from a candidate list of ventilation strategies, the strategies that provide the most efficient evacuation of H_2S from the rectangular confined-space manure tank used in this study. Identified in this study were the best ventilation strategies for each of the fully slotted, partially slotted, and solid cover types for both the high and low air exchange rates. This research leads to the following conclusions:

- For the rectangular manure storage tank and the ventilation strategies used in this study, gas concentrations at the centerline of the tank were representative of concentrations across the width of the tank for fully slotted, partially slotted, and solid cover cases.
- Values of T_{25} for H_2S concentration reduction were significantly different ($p < 0.05$) between fan location, grid, and level for the rectangular confined-space manure storage configuration used in this study with fully slotted, partially slotted, and solid cover types. In addition, T_{25} values were significantly different ($p < 0.05$) between air exchange rates for the rectangular confined-space manure tank with the solid cover type.
- The mean T_{25}, T_{pel}, and $T_{pel-max}$ for H_2S concentration reduction indicated that case I (fan centrally located on fully slotted cover storage cover, fig. 7a) was the best of the candidate ventilation strategies investigated for the fully slotted cover type at both the high and low air exchange rates.
- The mean T_{25}, T_{pel}, and $T_{pel-max}$ for H_2S concentration reduction indicated that case I (fan centrally located on storage cover, fig. 7a) was the best of the candidate ventilation strategies investigated for the partially slotted cover type at the high air exchange rate. The mean T_{25}, T_{pel}, and $T_{pel-max}$ indicated that case III (fan located at midpoint between sidewalls and along one end wall, fig. 7a) and case I were the best of the candidate ventilation strategies investigated for the partially slotted cover type at the low air exchange rate. Case III was selected as the best ventilation strategy for the low air exchange rate based on the mean T_{pel} value ranking.
- The mean T_{25}, T_{pel}, and $T_{pel-max}$ for H_2S indicated that case III (fan located at midpoint between sidewalls and along one end wall of the solid cover system and with outlet located at opposite end wall, fig. 7b) was the best of ventilation strategies investigated for the solid cover type at both the high and low air exchange rates.
- Hydrogen sulfide evacuation of rectangular confined-space manure storages when subjected to forced-air ventilation immediately after cessation of manure agitation is characterized by a short unstable transition time period followed by a non-linear gas reduction trend in semi-log space.
- A database of H_2S concentration reduction versus ventilation time, at all the sampling locations along longitudinal centerline of the tank (five girds) at the upper and

the lower levels, was developed for the best ventilation strategy identified for each cover type. This database is available for validating CFD modeling protocols for simulating evacuation of contaminant gases from confined-space manure storage facilities.

Acknowledgements

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Appendix

Table A1. T$_{25}$ values for H$_2$S reduction for the fully slotted cover cases.[a]

		T$_{25}$ (s)			
		Lower Level		Upper Level	
Case	Grid	High AC[b]	Low AC[b]	High AC	Low AC
	1	35	35	35	36
	2	30	41	31	40
I	3	25	40	26	42
	4	29	37	29	37
	5	40	29	42	28
	1	50	65	37	53
	2	47	59	33	44
II	3	61	74	35	51
	4	56	61	42	49
	5	56	64	40	51
	1	60	76	35	47
	2	73	64	34	45
III	3	50	68	33	47
	4	75	61	33	27
	5	72	73	30	47
	1	56	61	54	57
	2	73	56	63	63
IV	3	66	59	68	54
	4	72	72	73	70
	5	182	75	126	59

[a] Level and grid shown in figure 4; T$_{25}$ values are averages of three replications for each treatment combination.
[b] Air exchange rate: high = 5 AC min^{-1}, low = 3 AC min^{-1}.

Table A2. T$_{25}$ values for H$_2$S reduction for the partially slotted cover cases.[a]

		T$_{25}$ (s)			
		Lower Level		Upper Level	
Case	Grid	High AC[b]	Low AC[b]	High AC	Low AC
	1	39	35	35	36
	2	36	41	31	40
I	3	35	40	26	42
	4	43	37	29	37
	5	47	29	42	28
	1	47	40	43	42
	2	28	31	30	31
II	3	26	56	23	50
	4	60	66	42	49
	5	54	65	36	49
	1	42	44	33	35
	2	36	46	29	37
III	3	37	41	30	33
	4	44	56	35	44
	5	44	56	35	44

(continued)

Table A2 (continuedf). T$_{25}$ values for H$_2$S reduction for the partially slotted cover cases.[a]

	1	37	59	16	30
	2	54	76	26	39
IV	3	67	83	31	42
	4	68	66	32	39
	5	61	69	34	46

[a] Level and grid shown in figure 4; T$_{25}$ values are averages of three replications for each treatment combination.
[b] Air exchange rate: high = 5 AC min^{-1}, low = 3 AC min^{-1}.

Table A3. T$_{25}$ values for H$_2$S reduction for the solid cover cases.[a]

		T$_{25}$ (s)			
		Lower Level		Upper Level	
Case	Grid	High AC[b]	Low AC[b]	High AC	Low AC
	1	74	54	52	49
	2	70	51	48	51
I	3	68	48	50	50
	4	70	61	42	41
	5	69	59	48	41
	1	45	60	45	54
	2	47	54	42	51
II	3	43	57	44	54
	4	51	57	48	57
	5	47	59	46	57
	1	42	51	42	51
	2	42	48	42	48
III	3	39	51	44	51
	4	48	61	50	60
	5	53	60	51	57
	1	49	55	49	60
	2	50	54	47	55
IV	3	48	54	51	57
	4	55	69	49	60
	5	54	69	51	60
	1	57	63	46	61
	2	57	63	43	65
V	3	55	61	45	63
	4	60	75	54	75
	5	60	80	51	80

[a] Level and grid shown in figure 4; T$_{25}$ values are averages of three replications for each treatment combination.
[b] Air exchange rate: high = 5 AC min^{-1}, low = 3 AC min^{-1}.