MANURE PIT-SAFETY VENTILATION DESIGN INFLUENCE ON HYDROGEN SULFIDE GAS CONTAMINATION IN ATTACHED BARNs

A Dissertation in Agricultural and Biological Engineering by Daniel W. Hofstetter

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ABSTRACT

Current manure pit-safety ventilation research has been limited to determining the minimum amount of time required to evacuate hazardous gases to allow human entry into confined-space manure storages. Commonly installed negative pressure pit ventilation systems reduce the level of contaminant gases in the manure pit air space, but the negative pressure pit fans are usually too small to effectively ventilate a manure pit for safety purposes prior to and during human entry. The preferred method for ventilating a manure pit for human entry is to use a positive pressure pit-safety fan that delivers fresh outside air into the manure pit air space at higher air exchange rates. However, there may be cases where ventilating for a longer duration at lower air exchange rates may be desirable, such as when a pit has a slotted cover and there is an occupied animal living space located above. In these cases, too high an air exchange rate in the pit can result in dangerous contaminant gas levels in a portion of the animal living space. This has been one barrier to adoption of pit-safety ventilation practices. It is not often convenient, or even possible, to relocate all of the animals because of the size of the herd and layout of the facility. For these cases, it is desirable to determine the best combination of pit-safety fan locations and pit air exchange rates that will result in satisfactory air conditions for welfare of the animals above yet ventilate the pit in a reasonable length of time for human entry. This research develops methodologies and protocols for evaluating barn air contamination hazards during positive pressure pit-safety ventilation and to demonstrate that manure pit ventilation configuration and fan capacity do influence the level of air contamination hazard in the barn.

Hydrogen sulfide (H₂S) gas decay was measured at several locations inside a swine nursery room during manure pit and room ventilation. A computational fluid dynamics (CFD) model of the nursery room was developed, and transient simulations of pit-safety and room ventilation were performed. Simulation results were compared to measured gas concentrations at 15 locations. Results indicated that the simulated temporal gas concentrations at 8 of 15 locations
agreed favorably (within validation criteria) after adjusting measured values for a first-order instrument response.

A trend observed during analysis of CFD simulation results for a given pit and barn shape and ventilation configuration (the same pit-safety fan location and flow rate with the same barn ventilation rate) with different uniform initial manure pit H2S gas concentrations (C₀) suggested that the ratio of concentration (C) at each time step during ventilation was equal to the ratio between the initial concentrations inside the manure pit. It was determined that C/C₀ scaling could be used to expand the results from one CFD simulation at one C₀ value to a wide range of C₀ values. The maximum error when comparing simulated to estimated C/C₀ values was ± 2.5% for the global maximum H₂S gas concentration over time.

Simulations were performed for a 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long) barn located above a full-sized manure pit with a fully-slotted cover. Tunnel ventilated and mechanically cross-ventilated barn configurations were studied to determine how manure pit-safety ventilation fan configuration (location and flow rate) affects the distribution of H₂S gas in the barn airspace during a barn and manure pit-safety ventilation event. Simulation results were analyzed to determine the affected area in the barn and the duration of time when the concentration of H₂S gas was 50 ppm or greater, the maximum H₂S concentration in the barn airspace, and how much time was required to reach safe H₂S gas entry levels in the manure pit. During pit-safety ventilation, the maximum concentration in portions of the airspace within both tunnel ventilated and mechanically cross-ventilated barns was equal to the initial manure pit H₂S concentration, requiring animals and personnel to be evacuated from those zones when C₀ ≥ 50 ppm.

The tunnel ventilated barn was divided lengthwise into five 6.10 m long × 12.20 m wide (20 ft long × 40 ft wide) quintiles for analysis. For the tunnel ventilated barn simulated in this study, animals should always be evacuated from the quintile nearest the tunnel ventilation barn exhaust fans when C₀ ≥ 50 ppm during pit-safety ventilation. When C₀ ≥ 200 ppm, the pit-safety
fan location at the longitudinal and transverse centerline of the barn resulted in more contaminated area in the barn overall and in the three center barn quintiles than all other cases, making this the worst choice for pit-safety ventilation fan location for tunnel ventilated barns. However, there were large contiguous clear areas in the three center barn quintiles for all other pit-safety fan locations and flow rates, including the case with no pit-safety fan, when the initial manure pit H$_2$S concentration was 300 ppm or lower. In general, pit-safety fan locations near the barn exhaust fans (counterflow locations) resulted in longer times to reach safe H$_2$S gas entry levels inside the manure pit compared to the case with no pit-safety fan, and pit-safety fan locations near the barn air inlets (parallel flow locations) resulted in shorter times. Parallel flow with the pit-safety fan located along the longitudinal centerline of the barn resulted in less overall contaminated area in the barn than all other cases as well as the case with no pit-safety fan.

The mechanically cross-ventilated barn was divided into five 2.44 m long × 30.49 m wide (8 ft long × 100 ft wide) quintiles for analysis. For the mechanically cross-ventilated barn simulated in this study, animals should be evacuated from at least portions of the quintile nearest the barn exhaust fans and the two quintiles farthest from the barn exhaust fans when $C_0 \geq 50$ ppm during pit-safety ventilation. However, there were large contiguous clear areas in the remaining two barn quintiles for all simulated cases when the initial manure pit H$_2$S concentration was 200 ppm or lower. All pit-safety fan locations and flow rates resulted in shorter times to reach safe H$_2$S gas entry levels in the manure pit compared to the case with no pit-safety fan.

This work demonstrates the potential for evaluating alternative pit-safety ventilation configurations to reduce the need for animal evacuation from portions of barns located above positive pressure safety ventilated manure pits. Parallel flow pit-safety fan locations were more effective for the tunnel ventilated barn, with more contamination near the barn exhaust fans and along the barn sidewalls. In general, parallel flow pit-safety fan locations with higher flow rates resulted in shorter times to reach safe H$_2$S gas entry levels in the manure pit, but increased contaminated area in the barn airspace. Animals do not need to be removed from barns during
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Chapter 1

Introduction and Literature Review

This literature review defines the state of the art of Computational Fluid Dynamics (CFD) for simulation of confined-space manure pit-safety ventilation under barns. First, background about confined-space manure storages in agriculture and related hazards is reviewed. Further literature is reviewed related to the parameters needed to simulate manure pit-safety ventilation using CFD. Finally, the state of the art of CFD in confined-space manure pit-safety ventilation summarizes the need for further research on this topic.

1.1 Confined-space manure storages in agriculture and related hazards

Many swine facilities built in North America during the 1970s were constructed with the animal living space located above slotted floors with under-barn manure storages (Donham, Yeggy, & Dague, 1988). While common in European dairy barns, slotted floor dairy barns are unlikely to become commonplace in the United States due to its varied climate (Cook, 2002). However, there are presently several companies that manufacture precast concrete slotted flooring sections and construct dairy barns with slotted flooring and under-barn manure storages across the U.S. These precast sections are offered in a waffle slat configuration (Figure 1.1), which consists of many short slot openings between slats, or a conventional slat configuration (Figure 1.2). The slots are typically oriented perpendicular to the length of the barn, but may be parallel for some applications. Agitation and pumping panels may be strategically located throughout the barn.
Dairy facilities constructed above full-sized manure storages typically have partially slotted floors, with solid covered areas located under the cow stalls and feeding areas (NRAES, 1997). Farrowing pig housing is often constructed with partially slotted floors located in the pen.
areas. These facilities are typically built above smaller manure storages located only under the slotted areas of the barn floor (Stanislaw & Muehling, 1997). However, this type of construction is less common since the cost is similar to that of a full-sized pit, and full-sized manure pits provide a much greater storage volume. Other types of swine facilities are built with totally slotted floors above a full-sized manure storage (Harmon, et al., 2001).

One advantage of under-barn manure storages is that they do not require additional land for manure collection and storage, resulting in available outside space for other buildings or for crop production. Another advantage of this type of manure storage system is that slotted floors provide a convenient means for transporting manure from the barn floor into the storage as animals push the manure through the floor openings passively when they walk on the floor. Manure is typically stored in these facilities for three to nine months prior to removal for land application. However, because the manure is stored in anaerobic conditions, environmental hazards arise from the release of manure gases from the manure pit into the animal living space above.

1.2 OSHA Permit-required Confined Spaces

The Occupational Health and Safety Administration (OSHA) defines a “confined space” as any space 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 (for example, tanks, vessels, silos, storage bins, hoppers, vaults, and pits are spaces that may have limited means of entry.); and (3) Is not designed for continuous employee occupancy.” (Occupational Safety & Health Administration, 1998)

A “permit-required confined space” as defined by OSHA is “a confined space that has one or more of the following characteristics: (1) Contains or has potential to contain a hazardous atmosphere; (2) Contains a material that has the potential for engulfing an entrant; (3) Has an
internal configuration such that an entrant could be trapped or asphyxiated by inwardly converging walls or by a floor which slopes downward and tapers to a smaller cross-section; or (4) Contains any other recognized serious safety or health hazard.” (Occupational Safety & Health Administration, 1998)

1.3 Manure gases and associated hazards

Manure undergoes a process of anaerobic biodegradation and releases many different gases during storage in manure pits. The four gases that are the most hazardous and are released in the largest quantities are hydrogen sulfide (H$_2$S), ammonia (NH$_3$), carbon dioxide (CO$_2$), and methane (CH$_4$) (Patni & Clarke, 1991). Hydrogen sulfide is generally considered the most dangerous of the four gases due to the relatively low concentrations that are immediately dangerous to life and health (IDLH). The highest documented levels of these four gases found in manure storage facilities are listed in Table 1.1. Zhao performed CFD simulations of manure pit-safety ventilation using the initial uniform pit gas concentrations shown in Table 1.1 for initial conditions inside the manure pit (Zhao, Manbeck, & Murphy, 2008). In Zhao’s simulations, H$_2$S required the longest duration of pit-safety ventilation time to reach safe exposure levels required for human entry into the manure pit (i.e., the other gases reached their safe exposure levels before H$_2$S).
Table 1.1. Highest documented NH$_3$, H$_2$S, CO$_2$, and CH$_4$ gas levels in manure storages.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Concentration</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$</td>
<td>270 ppm</td>
<td>(Patni &amp; Clarke, 2003)</td>
</tr>
<tr>
<td>H$_2$S</td>
<td>10,000 ppm</td>
<td>(De Belie et al., 2000)</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>450,000 ppm</td>
<td>(De Belie et al., 2000)</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>700,000 ppm</td>
<td>(De Belie et al., 2000)</td>
</tr>
</tbody>
</table>

The release rate of H$_2$S gas from stored manure is affected by temperature. H$_2$S generation from stored manure is slower during winter months (below 18°C), and typical winter ventilation rates are adequate to prevent H$_2$S from building up to dangerous levels in barns (Donham et al., 1988). The higher barn ventilation rates used during summer months help to compensate for the higher gas production rate during the summer (Patni & Clarke, 1991). H$_2$S is released at much higher rates during manure pit agitation and pumping operations. Zhao (2006; Zhao et al., 2008) showed that H$_2$S emission rates that were ten times higher than measured emission rates had only a small effect (< 5%) on the ventilation time required to reach allowable exposure levels in CFD simulations. This suggests that, in the absence of manure agitation, the H$_2$S emission rate was not a significant factor in evacuating gas from the manure storage at the air exchange rates supplied by the pit-safety ventilation fan.

It is a common assumption that heavier (than air) gases will accumulate near the floor while lighter (than air) gases rise to the ceiling. However, gases have a high tendency to diffuse (Muehling, 1970). Studies have shown that the concentrations of carbon dioxide and hydrogen sulfide, which are both heavier than air, were nearly equal at the floor and ceiling levels inside a cattle shed (Norén et al., 1967). This was further substantiated by Brannigan & McQuitty (1971), who concluded that light and heavy gases have approximately the same horizontal and vertical distribution patterns in a ventilated airspace.
1.4 Contaminant gas exposure limits

Maximum allowable human exposure concentrations (typically expressed in ppm) have been defined for the contaminant gases typically found in confined-space manure storages. These limits have been set to provide guidelines for keeping workers safe from the health effects of exposure to toxic substances. The Permissible Exposure Limit (PEL) for a contaminant gas is usually given as a time-weighted average (TWA), which is the average exposure over a nominal eight-hour time limit (one workday). The time required to reach the permissible exposure limit (\( T_{pel} \)) is the minimum duration of time required to ventilate a confined-space before a contaminant gas will decay to the PEL.

The Occupational Safety and Health Administration (OSHA) is a federal agency that is responsible for the enforcement of occupational safety and health regulations in the United States. According to OSHA Standard 1910.1000(b) (Occupational Safety & Health Administration, 1997), the acceptable ceiling concentration for human worker exposure to Hydrogen Sulfide (\( \text{H}_2\text{S} \)) gas is 20 ppm for an 8-hour workday. If no other measurable exposure has occurred, the acceptable peak concentration above the ceiling is 50 ppm for a maximum duration of 10 minutes. The previous 1989 OSHA PEL for \( \text{H}_2\text{S} \) was 10 ppm (TWA). The exposure limits defined by OSHA are enforceable, but more conservative limits have been suggested by others.

The U.S. National Institute for Occupational Safety and Health (NIOSH) is the federal agency that is responsible for making research-based recommendations for the prevention of workplace injury and illness. The NIOSH Recommended Exposure Limit (REL) for \( \text{H}_2\text{S} \) is 10 ppm with a 10-minute ceiling (National Institute of Occupational Safety and Health, 2007). The NIOSH-defined concentration of \( \text{H}_2\text{S} \) that is considered immediately dangerous to life and health (IDLH) is 100 ppm. The OSHA regulation 1910.134(b) (Occupational Safety & Health Administration, 1998) defines IDLH as "an atmosphere that poses an immediate threat to life,
would cause irreversible adverse health effects, or would impair an individual's ability to escape from a dangerous atmosphere."

The American Conference of Governmental Industrial Hygienists (ACGIH) is a professional association that makes scientific recommendations to occupational health and safety professionals. The ACGIH recommends a threshold limit value (TLV) for H$_2$S of 1 ppm as an 8-hour time weighted average, and a short-term exposure limit (STEL) of 5 ppm (American Conference of Governmental Industrial Hygienists, 2007). A Threshold Limit Value (TLV) is the maximum concentration to which humans may be repeatedly exposed during a period of eight hours (one workday) over a lifetime without experiencing any adverse health effects. A Short-Term Exposure Limit (STEL) is the maximum concentration a worker may be exposed to over a 15 to 30 minute time period during a single eight-hour work day.

1.5 Animal health issues related to under-barn manure storages

Animal health problems associated with manure gases in barns from under-barn manure storages include irritation of the eyes, mucous membranes, and respiratory tract. More serious problems include asphyxiation due to high concentrations of CO$_2$ and death due to high concentrations of H$_2$S (Donham et al., 1977).

Threshold limits for animals raised in confinement housing may be lower than those published for humans, since the animals are exposed to conditions inside the barn 24 hours a day (Muehling, 1970). Animals that are exposed to a continuous level of H$_2$S of 20 ppm may develop a fear of light, nervousness, and loss of appetite (Holmes, Bickert, & Brugger, 1990). Young animals may be even more sensitive to the effects of toxic gases than mature animals (Taiganides & White, 1968). Since no enforceable recommended exposure limits currently exist for animals, the limits for humans are typically used.
1.6 Methods of ventilating barns and pits

Barns must be ventilated to maintain optimal environmental conditions for the animals that live within. A properly designed ventilation system provides air exchange inside the barn for the purpose of supplying fresh air while maintaining the levels of indoor air temperature, humidity, and airborne contaminants within desired limits (ASABE, 2017a).

Barn ventilation systems are either natural, mechanical, or some combination of the two (Holmes et al., 1990). Three types of ventilation systems commonly used for confined animal housing are natural, tunnel, and cross ventilation systems. “Naturally ventilated” (NV) barns are ventilated by ambient outdoor wind and thermal buoyancy forces. The barn is typically oriented such that the prevailing ambient wind enters approximately perpendicular to one sidewall and moves air laterally through the barn. When ambient wind conditions are not favorable for natural ventilation due to obstructions, or at sites where the natural topography makes it impossible to orient the barn to take advantage of prevailing winds, barns are usually ventilated mechanically with fans. Mechanical ventilation is also commonly used for animals that require more carefully controlled thermal environments. “Tunnel ventilated” (TV) and “cross-ventilated” (CV) barns typically rely on negative pressure mechanical ventilation from exhaust fans to draw air longitudinally and/or laterally through the barn, respectively. Although less common, some barns are constructed with positive pressure mechanical ventilation systems.

1.6.1 Natural ventilation

Natural ventilation systems depend on wind and thermal air buoyancy to provide air exchange and air movement throughout the barn (Holmes, Bickert, & Brugger, 1989). Airflow through the building is controlled by varying the height of the inlet and outlet openings along the barn by means of adjustable-height curtain sidewalls. A ridge vent allows for ventilation by natural convection during winter months when the curtain sidewalls are nearly closed to limit
freezing wind from entering the barn. Naturally-ventilated barns are carefully sited so that sidewalls are nearly perpendicular to the prevailing wind direction. Figure 1.3 shows a typical naturally ventilated barn.

![Diagram of a naturally ventilated barn]

Figure 1.3. A typical naturally ventilated barn.

Natural ventilation has the potential to provide much greater air exchange rates through the barn when compared to mechanically-ventilated barns based on average wind speeds throughout the year and the area of large barn sidewall openings. However, during periods of extreme summer conditions (slow or stagnant wind combined with hot, humid weather), natural ventilation may not maintain the minimum air exchange rates required inside a barn. Supplemental cooling fans are often used in naturally-ventilated barns to provide air movement across the animals when ambient wind conditions are not favorable. However, these fans do not have a large effect on the direction of bulk airflow through the barn, and the direction of interior airflow is very similar to that of the outside wind (Stowell, et al., 2001).
1.6.2 Tunnel ventilation

Tunnel ventilation is a negative pressure mechanical ventilation system which uses exhaust fans to draw air longitudinally through a barn for the purpose of providing concurrent air movement and air exchange (Gooch & Timmons, 2000). The exhaust fans are installed at one end of the barn. Barn sidewall and ridge openings are completely closed, and the other end of the barn has large air inlets so that the fans can create a “tunnel” airflow effect. Figure 1.4 shows a typical tunnel ventilated barn.

![Figure 1.4. A typical tunnel ventilated barn.](image)
1.6.3 Cross-ventilation

Cross-ventilation is a negative pressure mechanical ventilation system which uses exhaust fans to draw air laterally across a barn. Exhaust fans are typically installed along one sidewall in barns up to 12.2 m (40 ft) wide (Figure 1.5), but may be installed along both sidewalls in barns that exceed this width. Fans may be installed in groups called “banks” or evenly-spaced along the sidewalls. Exterior air inlets are commonly located along the length of the sidewalls, just below the eaves (Figure 1.6). In barns that are more than 12.2 m (40 ft) wide, additional air inlets are typically provided in the ceiling.

![Diagram of cross-ventilation system](image)

Figure 1.5. A typical cross-ventilated barn.
1.6.4 Ventilating manure pits to reduce entry risk

An engineering standard currently exists for the ventilation of a limited set of stand-alone or underbarn confined-space manure storages to reduce entry risk. ANSI/ASABE S607 (ASABE, 2017b) addresses specific ventilation strategies which include pit-safety ventilation fan location, outlet location, air exchange rate, and required ventilation times to reduce the levels of contaminant gases in empty confined space manure storages to below ACGIH defined TLVs for hydrogen sulfide, carbon dioxide, and methane, and to replenish oxygen levels from 0% to 20% by volume.

1.6.5 Ventilating barns above manure pits

Anytime a barn is located above a manure pit, the barn must be well-ventilated prior to pit-safety ventilation to prevent levels of toxic gases from building up inside the barn airspace. For a mechanically ventilated barn, the required ventilation rate is the hot weather maximum,
which should be calculated from ASAE Standard EP270.5 (ASABE, 2017a) provisions.

Whenever animals are present, ASABE Standard S607 (ASABE, 2017b) states that the barn ventilation system must be run at the hot weather maximum air exchange rate for a fully-stocked facility for 5 minutes prior to the start of manure pit-safety ventilation, and continue for the entire duration of manure pit-safety ventilation. If the hot weather maximum air flow rate cannot be provided, all animals must be removed from the barn prior to manure pit-safety ventilation.

Recent CFD simulations by the author (Manbeck et al., 2016) suggest that at least a small portion of most barns above manure pits experience some undesirable levels of H\textsubscript{2}S gas when initial gas concentrations inside the manure pit are greater than the acceptable ceiling exposure limit, even if only for a short duration of time. However, in many cases it is impractical, if not impossible, to remove all of the animals from a barn due to the labor required to relocate the animals temporarily and the associated loss of productivity. Most farms do not have the additional space or facilities required to contain the animals, even for a short duration of time. For these reasons, farmers do not want to evacuate animals from the barn, and are unlikely to do so even if recommended. This appears to be a major impediment to the adoption of the manure pit-safety ventilation standard prior to entry.
1.6.6 Computational fluid dynamics

Computational Fluid Dynamics (CFD) simulation programs are regularly used to predict air movement and pollutant distributions in ventilated agricultural buildings (Norton et. al., 2007). The majority of contemporary CFD programs use the Finite Volume Method to solve the Reynolds-Averaged Navier-Stokes (RANS) equations. The Reynolds averaging procedure introduces additional terms into the equations known as Reynolds stresses. To close the system of equations, turbulence models must be employed. The standard $k$-$\varepsilon$ model was developed for isotropic turbulent flows (Launder & Spalding, 1974), and is a commonly available option in commercial CFD programs. Although the standard $k$-$\varepsilon$ model is numerically stable when simulating indoor airflow, predicted results do not always agree with measured data (Q. Chen, 1995). However, Zhao (2006) showed that the standard $k$-$\varepsilon$ model yields acceptable results when simulating manure pit-safety ventilation for the purpose of reducing the concentration of manure gases inside the pit prior to entry.

1.6.7 Survey of available CFD codes

Many commercially available CFD codes exist, and they all function similarly. They all solve some time-averaged form of the Navier Stokes Equations for fluid flow using the finite volume method. Most commonly, the Reynold’s Averaged Navier Stokes (RANS) Equations are solved. Some CFD codes use Cartesian meshing with cuboid mesh cells, while others employ body-fitted meshing algorithms with hexahedral mesh cells. Model geometry creation is one area where the various CFD codes have substantive differences. In CFD codes that are not fully-embedded into a Computer-aided Drafting (CAD) program, geometry creation and definition of boundary conditions can be a very tedious process. Another area where there are substantial differences between CFD codes is in the post-processing and generation of graphical output from the simulation results. Both Fluent (Ansys, 2009) and Phoenics (CHAM, 2005) allow for a
greater selection of turbulence models, and Fluent allows for manual entry of additional equations that define other processes that may affect the fluid flow properties. However, those capabilities were not deemed necessary for this research.

1.6.8 SolidWorks Flow Simulation

SolidWorks Flow Simulation (SWFS) (Dassault Systèmes Solidworks Corporation, 2015a) was selected for this research project to simulate the evacuation of hydrogen sulfide (H₂S) gas during forced ventilation from a confined-space manure storage located under a ventilated barn. The following functional considerations were considered when selecting SolidWorks Flow Simulation:

1. It is design-oriented, and more likely to be used in a typical design office than some of the other CFD programs.
2. License fees are lower compared to other CFD software packages.
3. Flow Simulation is fully integrated into SolidWorks – the modeling, meshing, solving, and post-processing (visualization of results, reporting, etc.) are all performed in a single package.
4. Since the CFD code is fully integrated into SolidWorks, 3D model geometry can be easily created and modified parametrically. Application of boundary and initial conditions in the flow project is also an easy task.
5. Models can have different geometric feature configurations, and parametric studies are possible.
6. Turbulence modeling is possible using the standard k-ε turbulence model.
7. Mixed species modeling is possible (air and other gases).
8. Both internal and external flows can be simulated.
9. Solution-adaptive meshing capabilities allow the mesh to be automatically refined in areas of the flow model where there are high velocity gradients, or optimized by combining multiple smaller cells with low velocity gradients into larger single cells.

10. Porous media can be used to represent distributed resistances to flow without creating an unnecessarily dense mesh associated with modeling extremely fine or complex geometry.

11. Perforated plates can be used at pressure openings in boundary conditions.

1.6.9 Governing equations

SWFS employs the finite volume (FV) method to solve the Favre-averaged Navier-Stokes (FANS) equations. A rectangular Cartesian coordinate system is used to spatially discretize the computational domain into control volumes (mesh cells) which are orthogonal to the X, Y, and Z axes. Physical variables for mesh cells are reported at the centroid of the control volumes. The governing equations are discretized using the integral forms of the conservation laws for mass, momentum, and energy. Second-order accurate implicit difference operators are used to approximate the spatial derivatives using an upwind approach. A first-order accurate implicit Euler scheme is used to approximate the time derivatives using a SIMPLE-like approach. The governing equations of the Favre-averaged Navier-Stokes equations and the standard k-ε turbulence model used in SWFS are given in Equations 1-1 to 1-23 (Dassault Systèmes Solidworks Corporation, 2015b):

Continuity equation:

\[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \]  \hspace{1cm} (1-1)
Momentum equation:

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) + \frac{\partial p}{\partial x_j} = \frac{\partial}{\partial x_j} (\tau_{ij} + \tau_{ij}^R) + S_i, \quad i = 1, 2, 3
\]  

Energy equation:

\[
\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_j} \left( u_j (\tau_{ij} + \tau_{ij}^R) + q_i \right) + \frac{\partial p}{\partial t} \frac{\partial \tau_{ij}}{\partial x_j} + \rho \varepsilon + S_i u_i + Q_{ij}
\]  

\[
H = h + \frac{u^2}{2}
\]

For Newtonian fluids:

\[
\tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right)
\]

Following the Boussinesq assumption:

\[
\tau_{ij}^R = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) - \frac{2}{3} \rho k \delta_{ij}
\]

\[
\mu_i = f_\mu \frac{C_i \rho k^2}{\varepsilon}
\]

\[
f_\mu = \left[ 1 - \exp(-0.0165R_T) \right]^2 \cdot \left( 1 + \frac{20.5}{R_T} \right)
\]

where

\[
R_T = \frac{\rho k^2}{\mu \varepsilon}
\]
\[ R_y = \frac{\rho \sqrt{k} y}{\mu} \] and \( y \) is the distance from the wall. \hfill (1-10)

Turbulent kinetic energy equation:

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho u_i k \right) = \frac{\partial}{\partial x_i} \left( \left[ \mu + \frac{\mu_t}{\sigma_k} \right] \frac{\partial k}{\partial x_i} \right) + S_k \] \hfill (1-11)

Dissipation rate of turbulent energy equation:

\[
\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho u_i \varepsilon \right) = \frac{\partial}{\partial x_i} \left( \left[ \mu + \frac{\mu_t}{\sigma_\varepsilon} \right] \frac{\partial \varepsilon}{\partial x_i} \right) + S_\varepsilon \] \hfill (1-12)

Where:

\[ S_k = \tau_{ij}^R \frac{\partial u_i}{\partial x_j} - \rho \varepsilon + \mu_t P_B \] \hfill (1-13)

\[ S_\varepsilon = C_{\varepsilon1} \frac{\varepsilon}{k} \left( f_1 \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \mu_t C_B P_B \right) - C_{\varepsilon2} f_2 \frac{\rho \varepsilon^2}{k} \] \hfill (1-14)

\[ P_B = -\frac{g_i}{\sigma_B} \frac{1}{\rho} \frac{\partial \rho}{\partial x_i} \] \hfill (1-15)

\[ f_1 = 1 + \left( \frac{0.05}{f_\mu} \right)^3 \] \hfill (1-16)

\[ f_2 = 1 - \exp\left( - R_T^2 \right) \] \hfill (1-17)
The values of the coefficients used in the standard \( k-\varepsilon \) model in SWFS are: \( C_{\mu} = 0.09 \), \( C_{\varepsilon 1} = 1.44 \), \( C_{\varepsilon 2} = 1.92 \), \( \sigma_{\varepsilon} = 1.3 \), and \( \sigma_k = 1.0 \). Where the Lewis number \( Le = 1 \), the diffusive heat flux \( q_i \) is defined as:

\[
q_i = \left( \frac{\mu}{Pr} + \frac{\mu_i}{\sigma_c} \right) \frac{\partial h}{\partial x_i}, \quad i = 1, 2, 3
\]

Concentration equation:

\[
\frac{\partial \rho y_m}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i y_m) = \frac{\partial}{\partial x_i} \left( \left(D_{mm} + D'_{mn}\right) \frac{\partial y_m}{\partial x_i} \right) + S_m
\]

(1-19)

In case of Fick’s diffusion law:

\[
D_{mn} = D \cdot \delta_{mn}, \quad D'_{mn} = \delta_{mn} \cdot \frac{\mu_i}{\sigma}
\]

(1-20)

The sum of species concentrations:

\[
\sum_m y_m = 1
\]

(1-21)

For Porous Media:

\[
S_i^{\text{porous}} = -k \delta_{ii} \rho u_j
\]

(1-22)

For Perforated Plates in Boundary Conditions:

\[
\Delta p = -\zeta \cdot \frac{1}{2} \rho \cdot u^2
\]

(1-23)

Where:

\( t = \text{time} \)

\( x_i = \text{coordinate in } i^{\text{th}} \text{ direction} \)
\(i, j, k\) (subscript) = spatial coordinates

\(p\) = mean pressure

\(u\) = fluid velocity

\(\rho\) = fluid density

\(S_i\) = mass-distributed external force per unit mass, \(S_i = S_i^{\text{porous}} + S_i^{\text{gravity}} + S_i^{\text{rotation}}\)

\(h\) = thermal enthalpy

\(Q_H\) = heat source or sink per unit volume

\(\tau_{ij}\) = viscous shear stress

\(q_i\) = diffusive heat flux

\(\delta_{ij}\) = Kronecker delta function (equal to unity when \(i = j\), 0 otherwise)

\(\mu\) = dynamic viscosity

\(\mu_t\) = turbulent eddy viscosity

\(k\) = turbulent kinetic energy

\(\varepsilon\) = dissipation rate of \(k\)

\(f_\mu\) = turbulent viscosity factor

\(P_B\) = turbulent generation due to buoyancy

\(g_i\) = component of gravitational acceleration in direction \(x_i\)

\(\sigma_B\) = constant (equal to 0.9)

\(C_B\) = constant (equal to 1 when \(P_B > 0\), 0 otherwise)

\(C_\mu, C_{\varepsilon1}, C_{\varepsilon2}\) = coefficients in the standard \(k-\varepsilon\) turbulence model

\(\sigma_c\) = diffusion coefficient in turbulence models for \(\varepsilon\)

\(\sigma_k\) = diffusion coefficient in turbulence models for \(k\)

\(q_i\) = diffusive heat flux

\(\sigma_c\) = constant (equal to 0.9)

\(\Pr\) = Prandtl number

\(y_m\) = concentration of \(m\)-th species
\[ D_{mn}, D'_{mn} = \text{molecular and turbulent matrices of diffusion} \]
\[ S_m = \text{rate of production or consumption of the } m\text{-th component} \]
\[ \zeta = \text{hydraulic resistance of holes in perforated plate} \]
\[ g_i = \text{component } i \text{ of the gravitation vector} \]

1.6.10 CFD research related to ventilation of manure storages

Pesce (2005) measured the concentration decay of \( \text{H}_2\text{S} \) gas during forced ventilation of an outdoor rectangular-shaped confined-space manure pit. Solid, partially-slotted, and fully-slotted covers were tested, and the pit-safety fan location was varied to determine which fan location resulted in reaching \( T_{pel} \) in the shortest duration of time for each type of cover at two different ventilation air exchange rates: 3 and 5 air-changes per minute (AC/min). Zhao (2006) developed CFD models based on the “best” fan locations identified by Pesce. A measurement grid approach was used during CFD simulations to determine \( T_{pel} \) for the entire manure storage. The simulated measurement grid was set up so that the grid point locations matched the actual locations of field measurements taken by Pesce during manure pit-safety ventilation trials. This approach allowed Zhao to compare simulation results to the field measurements by Pesce, and to demonstrate that CFD simulations could be used to predict the amount of time required to ventilate confined-space manure storages to \( T_{pel} \). However, it was still possible for other manure storage locations (such as the lower corners located farthest from the fan) to have \( \text{H}_2\text{S} \) concentrations greater than 10 ppm even after \( T_{pel} \) was reached at all grid measurement locations.

Neither the Pesce nor Zhao studies included a case with a barn located above the manure pit. In the case of a barn located above a manure pit, where gas is removed from the pit by means of forced ventilation, it is likely that an interaction exists between pit-safety fan location, pit-safety fan air flow rate (\( Q_{\text{pit}} \)), and the air flow rate of the barn ventilation system (\( Q_{\text{barn}} \)). While
high air exchange rates will result in more rapid evacuation of gases from manure pits, they are likely to result in higher levels of toxic gases being forced into the animal breathing space of a barn during manure pit-safety ventilation. Depending on the barn type and ventilation system configuration, a pit-safety fan location that is not the “best” in terms of reaching $T_{pel}$ in the shortest possible time may help to minimize the levels of hazardous gases exhausted into the barn airspace, and the extent of the barn area that is affected. There may also be pit-safety fan locations that result in an increased level of hazard in the barn airspace. An example of this is the ventilation of a full-sized manure pit located under a tunnel ventilated barn where the pit exhaust outlet is located upwind of the barn ventilation fans (Figure 1.7). In this case, all of the contaminated air exhausted from the pit would flow directly into the barn airspace near the barn fresh air inlets, then travel through the entire barn before being exhausted from the barn exhaust fans.

Figure 1.7. Tunnel ventilated barn with pit exhaust outlet located at open-end of barn.
1.6.11 Validation of CFD models

Validation of CFD models is performed to ensure that simulations agree with physical reality (Chen & Srebric, 2002). Validation involves comparing simulated values with real-world measurements from the physical system being modeled. The criteria used for validation of a CFD model depend on the particular application and parameters of interest. In the case of CFD models used to simulate forced ventilation of manure storages, the most important parameters are the prediction of H$_2$S gas concentrations throughout the storage and the duration of time required to evacuate H$_2$S to a safe level prior to human entry. Therefore, the validation criteria used for this application must account for both the spatial and temporal distribution of H$_2$S gas during ventilation.

The American Society for Testing and Materials (ASTM) standard D 5157-97 (ASTM, 2008) describes methods and statistical criteria for evaluating the accuracy of air concentrations predicted by indoor air quality models. The criteria can be used to compare results from a computer simulation to experimental measurements, or to compare the results between different simulations. According to the standard, an air quality model can be considered adequate if the following six criteria are met when comparing predicted versus observed concentration values:

1. A correlation coefficient $\geq 0.9$.
2. A regression slope between 0.75 and 1.25.
3. A regression intercept $\leq 25\%$ of the average measured concentration.
4. A normalized mean square error (NMSE) $\leq 0.25$.
5. A normalized fractional bias (FB) of mean concentrations $\leq 0.25$.
6. A similar index of bias (FS) based on concentration variance $\leq 0.5$.

These criteria provide a basis for deciding whether a simulation yields acceptable results. However, because they were developed for experiments performed under strictly-controlled
laboratory conditions, these criteria may be too stringent for validation of CFD models against data obtained from on-farm or other field measurements where atmospheric conditions are difficult to control (Zhao, 2006).

To validate the predicted spatial distribution of H$_2$S gas inside a manure tank (from CFD simulation results) against on-farm H$_2$S concentration measurements, Zhao (2006) used a set of relaxed statistical validation criteria that included the first three criteria listed above from the ASTM D 5157-97 standard. To ensure that the transient decay of H$_2$S gas was predicted with reasonable accuracy, an additional criterion was added. The complete set of criteria used by Zhao (2006) is listed below:

1. A correlation coefficient $\geq 0.9$.
2. A regression slope between 0.75 and 1.25.
3. A regression intercept $\leq 25\%$ of the average measured concentration.
4. A difference $\leq 10\%$ between predicted and measured duration of time required to ventilate the manure storage until the H$_2$S concentration $\leq 10$ ppm.

This is a simple method of comparing the shape of two transient decay curves for concentration data at a single location and estimating the differences.

**1.6.12 State-of-the-art of CFD in underbarn confined-space manure pit ventilation**

Current manure pit-safety ventilation research has been limited primarily to determining the amount of time required to evacuate hazardous gases to the human permissible exposure limit from confined-space manure storages. Zhao (2006) used CFD to predict the amount of time required to ventilate confined-space manure storages to reduce the level of H$_2$S gas to safe levels for human entry. This study was limited to stand-alone manure storages, and did not consider cases where the manure storage is located under a barn. However, there may be cases where
ventilating for a longer duration at lower air exchange rates may be desirable, such as when a pit has a slotted cover and there is an occupied animal living space located above. In these cases, too high an air exchange rate in the pit can result in dangerous contaminant gas levels in the animal living space. This has been a barrier to adoption of pit-safety ventilation practices because it is not often convenient or even possible to relocate all of the animals depending on the size of the herd and layout of the facility. For these cases, it is desirable to determine the best combination of pit-safety fan locations and pit air exchange rates that will result in safe air conditions for the animals above yet ventilate the pit in a reasonable length of time for human entry. Further research is needed to establish guidelines to identify the portions of the above-pit barns that need to be evacuated during manure pit-safety ventilation. Pit-safety ventilation strategies that reduce the portion of the barn requiring evacuation must also be identified.
Chapter 2
Objectives and Methodology Overview

2.1 Research hypotheses, overall goal, and specific objectives

Hypotheses

$H_0$: For a given initial concentration of $\text{H}_2\text{S}$ gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate ($\text{m}^3/\text{s}$), there is no positive pressure pit-safety ventilation air flow rate ($\text{m}^3/\text{s}$) that will result in dangerous conditions ($\text{C H}_2\text{S} \geq 50$ ppm for 10 min) in selected contiguous barn areas when the initial pit concentration is greater than 50 ppm.

$H_1$: For a given initial concentration of $\text{H}_2\text{S}$ gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate ($\text{m}^3/\text{s}$), there exists a maximum pit air ventilation flow rate ($\text{m}^3/\text{s}$) that can be used without raising the concentration of $\text{H}_2\text{S}$ gas in selected contiguous barn areas (measured at 0.15 m (6 in.) above the floor) above a threshold level of 50 ppm ($\text{C H}_2\text{S} \geq 50$ ppm for 10 min), yet will evacuate the gas inside the pit within 30 minutes.

$H_2$: For a given initial concentration of $\text{H}_2\text{S}$ gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate ($\text{m}^3/\text{s}$), there exists a minimum effective pit-safety ventilation air flow rate ($\text{m}^3/\text{s}$) that will result in $T_{\text{pel}}$ (10 ppm) being reached in a defined acceptable maximum amount of time (30 minutes, or another preselected reasonable time limit) without creating dangerous conditions ($\text{C H}_2\text{S} \geq 50$ ppm for 10 min) in selected contiguous barn areas (measured at 0.15 m (6 in.) above the floor).
The overall goal of this study was to develop methodologies and protocols for evaluating barn air contamination hazards where H$_2$S gas concentration equals or exceeds 50 ppm in the animal living space inside barns with fully slotted floors located above confined-space manure pits during positive pressure pit-safety ventilation and to demonstrate that manure pit ventilation configuration and fan capacity do influence the level of air contamination hazard in the barn. The specific objectives were:

1. (Phase I) To demonstrate that SolidWorks Flow Simulation (SWFS) is suitable for research use and to develop a validated CFD model that can be used to simulate the selected pit and barn configurations that will be considered for this study.

2. (Phase II) To identify zones within tunnel ventilated barns with fully-slotted floors located above full-sized mechanically-ventilated manure pits that must be evacuated for ratios of $Q_{\text{pit}}/Q_{\text{barn}}$ during positive pressure safety ventilation of the manure pit.

3. (Phase III) To identify zones within mechanically cross-ventilated barns with fully-slotted floors located above full-sized mechanically-ventilated manure pits that must be evacuated for ratios of $Q_{\text{pit}}/Q_{\text{barn}}$ during positive pressure safety ventilation of the manure pit.

4. (Phase IV) To develop a methodology that can be used by engineers to design manure pit-safety ventilation systems that reduce the risk of creating hazardous conditions inside the barn during pit-safety ventilation.

5. To provide recommendations for revision of the animal evacuation provisions of ANSI/ASABE S607.

2.2 Methodology overview

The research methodology was divided into four phases that correspond to the first four research objectives. Phase I focused on demonstrating that SolidWorks Flow simulation was
suitable for use as a research tool and to develop a validated CFD model to perform simulations during Phases II and III. Phase II focused on supporting the main hypotheses for tunnel ventilated barn ventilation configurations and a full-sized manure pit with a fully slotted cover. Phase III extended the supported hypotheses for cross-ventilated barns with full-sized manure pits with a fully slotted cover. A methodology was then developed in Phase IV based on the results from Phases II and III. This methodology can be used to design manure pit-safety ventilation systems that result in the least contaminated air conditions for the animals above yet ventilate the pit for human entry in a reasonable length of time. Detailed experimental design and methods used for each phase of the research project are presented in individual chapters of this dissertation.
Chapter 3

Phase I Swine Facility Experiment

3.1 Introduction

H$_2$S gas decay was measured at several locations inside a nursery room during manure pit and room ventilation. Since the nursery room study was a field study, the initial conditions in the room could be monitored, but not perfectly controlled. The collected data were subsequently used in the research project CFD validation efforts. The purpose of this chapter is to describe the ventilation experiment that was performed during Phase I of this research project and to present the measured data set that was post-processed for later CFD model validation.

3.2 Materials and methods

This section describes the facility, equipment, and gas monitors used for the ventilation experiment. First, the nursery room geometry and operating conditions were measured. A CFD model was created, and a preliminary simulation was performed to predict the flow conditions and spatial gas distribution during manure pit-safety ventilation. Gas monitors were placed in critical locations identified in the simulation results, and a trial experiment was performed to assess how well the CFD model represented the physical system. Based on the trial, some additional equipment and gas monitors were added to the experimental setup. The full ventilation experiment was then performed, and the measured data set was processed and examined.

3.2.1 Experimental facility dimensions and details

A physical experiment was performed in a ventilated nursery room (#3 in Figure 3.1) located at the Penn State swine facility in State College, PA. The nursery room houses up to 120
piglets from four to nine weeks in age. The piglets are separated into six pens and live in the room for 35 days before they are removed. The room is then cleaned and sanitized in preparation for the next litter of piglets.

![Plan view layout of Penn State swine facility.](image)

The nursery room was 11.1 m long × 3.7 m wide × 2.4 m high (36.4 ft × 12.1 ft × 7.9 ft). There was an 11.1 m × 2.8 m × 0.9 m deep (36.4 ft × 9.2 ft × 3.0 ft) manure pit located beneath a fully-slotted floor made up of sections of 0.46 m × 0.61 m (18 in. × 24 in.) grating. The manure pit had a solid 0.41 m (16 in.) high divider wall extending longitudinally at the centerline from the end wall closest to the room exhaust fans to within 1.83 m (6 ft) of the opposite end wall. The
manure depth was 0.43 m (17 in.) when testing was performed. Pull-plug outlets were located at the bottom of the manure pit on either side of the divider wall at the end of the pit near the room exhaust fans. The room contained six 1.83 m (6 ft) wide pens divided by steel fencing. The partition fencing was 85 percent unobstructed and offered minimal restriction of air flow through the nursery room. All animals were removed from the nursery room prior to performing the experiment. Figure 3.2 is a dimensioned schematic of the nursery room. Figure 3.3 is a photograph of the nursery room.

Figure 3.2. Schematic of Penn State swine facility nursery room #3.

Notes: Feeders and lighting are not shown; longitudinal manure pit divider wall not shown because it was submerged below the manure surface.
Each pen contained a feeder that was hung from the pen divider fencing. Two heaters were located in the room. A row of fluorescent lighting was hung from the ceiling at the center of the room width.

The floor grating had 42% open area, and the top of the grating was located 102 mm (4 in.) above the top of the concrete walkway. Figure 3.4 is a picture of a typical section of the floor grating.
The nursery room was mechanically ventilated, with two exhaust fans located on the outside wall at one end of the room. The fans were equipped with shutters that closed when the fans were not operating. The fan specifications are listed in Table 3.1.

### Table 3.1. Rated barn exhaust fan specifications.

<table>
<thead>
<tr>
<th>Fan</th>
<th>Nominal Diameter</th>
<th>Flow Rate (Rated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF5</td>
<td>0.51 m (20 in.)</td>
<td>1.40 m³/s (2,969 cfm)</td>
</tr>
<tr>
<td>EF7</td>
<td>0.41 m (16 in.)</td>
<td>0.64 m³/s (1,349 cfm)</td>
</tr>
</tbody>
</table>

#### 3.2.2 Barn fan outlet velocity

The small barn fan outlet velocity was measured following the procedure detailed in Wheeler & Botcher (1995) to obtain the outlet velocity used as a boundary condition in the CFD simulation. Several fan outlet velocities were measured across the face, and the average was used. The fan areas were calculated from measured fan diameters, and the resulting flow rates were calculated using area and the average measured velocities (Table 3.2).
Table 3.2. Measured fan air velocities and calculated flow rates.

<table>
<thead>
<tr>
<th></th>
<th>Measured Outlet Diameter m (ft)</th>
<th>Calculated Area m² (ft²)</th>
<th>Average Measured Outlet Velocity m/s (ft/s)</th>
<th>Calculated Flow Rate m³/s (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Fan² (EF5)</td>
<td>0.47 (1.54)</td>
<td>0.17 (1.87)</td>
<td>7.9 (26.03)</td>
<td>1.4 (2,915)</td>
</tr>
<tr>
<td>Small Fan (EF7)</td>
<td>0.37 (1.21)</td>
<td>0.11 (1.15)</td>
<td>5.8 (18.92)</td>
<td>0.6 (1,302)</td>
</tr>
<tr>
<td>Pit-safety Fan</td>
<td>0.20 (0.67)</td>
<td>0.03 (0.35)</td>
<td>6.1 (20.05)</td>
<td>0.2 (420)</td>
</tr>
</tbody>
</table>

1. Calculated from measured velocity and area, \( Q = V \times A \).
2. The large fan was measured and listed for reference, but was not used during the experiment.

3.2.3 Room air curtain inlet velocity

There was a 0.29 m (11.5 in.) high inlet slot located above the door spanning the width of the room. The air inlet had a curtain that was fixed at the top, with the free end weighted by a plastic pipe that hung down and sealed the inlet opening shut when the room exhaust fan was not operating. The curtain lifted open during room exhaust fan operation (Figure 3.5). With the small room exhaust fan and the pit-safety ventilation fan operating, the opening between the bottom of the curtain and the top of the baffle was 6.4 mm (0.25 in.). The inlet velocity was measured at several locations below the length of the curtain and averaged. The average measured inlet velocity below the curtain was 0.92 m/s (181 ft/min). The equivalent curtain inlet air flow rate, calculated from the curtain opening dimensions and the measured air velocity, was 0.021 m³/s (45 cfm).
The nursery room ceiling consisted of perforated corrugated steel, which served as an additional fresh air inlet. The perforations had a diameter of 12.7 mm (0.5 in.) and were spaced evenly on a 51.0 mm × 0.15 m (2 in. × 6 in.) grid. There was a ducted negative-pressure pit ventilation fan that exhausted pit gases to the outside. This fan was turned off and sealed shut with a polyethylene bag while taking gas measurements during pit-safety ventilation (Figure 3.6).
Figure 3.6. Nursery Room #3, blocked-off negative pressure pit fan, and barn exhaust fans.
3.2.4 Pit-safety ventilation fan

A portable Allegro Model 9514 (Allegro Industries, Piedmont, SC) ventilation fan with an attached outlet hose was used for pit-safety ventilation (Figure 3.7). The fan was driven by a 120V, 0.25 kW (1/3 HP) electric motor, and had a rated free air delivery of 0.6 m³/s (1,275 cfm).

![Portable pit-safety ventilation fan](image)

Figure 3.7. Portable pit-safety ventilation fan.

3.2.5 Gas monitor details

The concentration of H₂S gas during ventilation of the nursery room was measured using a combination of MX6 iBrid, Tango TX1, M40, and Ventis MX4 gas monitors manufactured by Industrial Scientific Corporation (Pittsburgh, PA) (Figure 3.8, Figure 3.9, Figure 3.10, and Figure 3.11, respectively). The monitors utilize an electrochemical sensor to detect H₂S gas. Each monitor had a built-in datalogger for recording the concentration of H₂S gas over time as the pit and nursery room were ventilated. The M40, MX4, and some of the MX6 gas monitors were equipped with a sampling pump with a tubing connection. However, a sampling tube was only
connected if the meter was used to measure gas concentration below the floor grating. Table 3.3 lists the measurement ranges and operating specifications for the meters.

Figure 3.8. MX6 iBrid multi-gas meter (a), shown with sampling pump installed (b).
Figure 3.9. Tango TX1 single-gas meter.

Figure 3.10. M40 sampling pump (a) and multi-gas meter (b)
Figure 3.11. Ventis MX4 multi-gas meter with sampling pump installed.
Table 3.3. Gas monitor specifications.

<table>
<thead>
<tr>
<th>Model</th>
<th>Measurement Range</th>
<th>Resolution</th>
<th>Temperature Range</th>
<th>Humidity Range</th>
<th>At temperature of calibration</th>
<th>Over full sensor temperature and RH ranges</th>
<th>Response Time</th>
<th>Data Logging Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>MX6 iBrid</td>
<td>0 to 500</td>
<td>0.1</td>
<td>-20 to 50°C</td>
<td>15 to 90%</td>
<td>5.0</td>
<td>15.0</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>Tango TX1</td>
<td>0 to 200</td>
<td>0.1</td>
<td>-50 to 50°C</td>
<td>15 to 95%</td>
<td>5.0</td>
<td>15.0</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>M40</td>
<td>0 to 500</td>
<td>1.0</td>
<td>-20 to 50°C</td>
<td>15 to 95%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ventis MX4</td>
<td>0 to 500</td>
<td>0.1</td>
<td>-20 to 50°C</td>
<td>15 to 95%</td>
<td>5.0</td>
<td>-</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>


3.2.6 Preliminary CFD simulation and trial experiment

A preliminary CFD simulation was performed for the nursery room with both room exhaust fans and the pit-safety ventilation fan operating to determine the best strategic placement of gas monitors. A uniform initial H$_2$S concentration of 100 ppm was assumed inside the pit, with atmospheric air everywhere else inside the room. The inlet curtain opening was set to 76 mm (3 in.) to match the measurements taken when both exhaust fans were operating. The simulation was run until the concentration of H$_2$S gas inside the manure pit was less than 1 ppm.
3.2.6.1 Trial gas monitor locations

Based on the results of the preliminary simulation, three TX1 units and two MX6 units were placed 0.15 m (6 in.) above the floor grating at the locations shown in Figure 3.12. Two M40 units were placed at the same locations as the MX6 units, with the inlet tubes located inside the manure pit 101.6 mm (4 in.) below the top of the floor grating. The simulation results showed large pockets of gas in the corners of the room closest to Fan EF7 and across from the pit-safety fan, so two of the MX6 units were placed in those locations at a height of 0.61 m (24 in.) above the floor grating (Figure 3.13). The simulation results also showed a gas pocket located near the center of the room, so a TX1 unit was placed 0.61 m (24 in.) above the floor grating in that location.

Figure 3.12. Trial gas measurement locations 0.15 m (6 in) above the floor.
3.2.6.2 Trial experiment

A trial ventilation experiment then was performed to determine if the preliminary CFD simulation predicted the behavior of the physical system well enough to justify meter placement and if the initial conditions could be adequately controlled during the experiment without any additional equipment.

3.2.6.3 Trial observations

During the trial run, all gas meters recorded $\text{H}_2\text{S}$ concentration continuously during agitation and ventilation events. Since the manure pit was left uncovered during manure agitation, the initial conditions were not well controlled and some $\text{H}_2\text{S}$ gas escaped through the floor grating during pit agitation, and the initial concentration above the floor was greater than zero at the start of pit and barn ventilation. As a result, the simulated transient gas concentration at each meter location could not be used to validate the preliminary CFD simulation.
However, the temporal and spatial trends observed in the recorded data were similar to the simulated trends. Meter alarms went off in the order that would be expected based on the simulated results, i.e. the gas cloud moved through the room during trial ventilation as predicted in the simulation. The gas pockets predicted in the simulation were supported by measurements recorded in those locations during the trial run.

Some changes and additions were made to the methodology used for the preliminary nursery room experiment based on the results of the trial run:

1. The pit-safety ventilation fan outlet duct had not been oriented vertically during the trial run, and directed air into the manure pit at an angle of approximately 45 degrees. The bend in the duct was close to the outlet end, and the air flow into the pit was not well developed. A vertical discharge pipe was added to straighten the flow and direct it vertically downward into the manure pit.

2. Since some gas escaped through the floor grating during manure agitation before the pit and barn ventilation fans were actuated, a pit cover was installed to constrain the gas inside the manure pit and minimize migration of manure pit gases into the nursery room prior to initiation of pit-safety ventilation.

3. The single agitation blower pipe did not remain stationary during blower operation and only effectively agitated the manure on one side of the divider wall in the pit. A weighted manifold was constructed to direct air to both sides of the divider wall, and a second blower was added to increase the output of the manifold to provide more aggressive manure agitation.

4. A larger number of gas meters were used during the experiment to capture more spatial variability in gas concentration during manure pit and room ventilation.
In addition the fresh air inlet concentration at the pit-safety ventilation fan was measured, and a gas monitor was placed in the hallway outside of the nursery room for safety purposes to determine if gas escaped from the nursery room into the hallway during the full experiment.

3.2.7 Pit-safety fan discharge pipe

To achieve a uniform fan air velocity, a 1.8 m (6.0 ft.) long section of 203.2 mm (8 in.) dia. SCH. 40 PVC pipe was used. The pit-safety ventilation fan was supported 1.6 m (63.5 in.) above the floor to avoid unnecessary bends in the ventilation duct. A 203.2 mm (8 in.) dia. 90° steel HVAC ducting elbow was used to transition from horizontal to vertical air discharge, and a vertical 1.8 m (72 in.) long, 203.2 mm (8 in.) dia. SCH. 40 PVC pipe was used to straighten the flow before it entered the manure pit (Figure 3.14).
The fan was located in the hallway outside of the nursery room. The fan inlet was facing away from the nursery room, drawing fresh air through an open exterior door located at the end of the hallway (Figure 3.15). The fan duct was extended from the fan through the nursery room doorway and connected to the 90° ducting elbow located at the top of the fan discharge pipe. The room doorway was sealed shut using plastic sheeting and masking tape to prevent unwanted air infiltration.
Figure 3.15. Pit-safety ventilation fan setup.

The fan discharge pipe was mounted to a 0.66 m × 0.51 m (26 in. × 20 in.) rectangular wooden plate that replaced one of the floor grating sections in the nursery room (Figure 3.16).
3.2.8 Pit-safety ventilation discharge pipe velocity

A vane Anemometer (Extech Instruments Model 407112) was used to measure the pit-safety ventilation discharge pipe inlet velocity in-place (Figure 3.16). Measurements were taken at three different locations across the inlet face and averaged according to procedure described in Wheeler and Botcher (1995). The average measured velocity was 6.1 m/s (1,203 ft/min).

3.2.9 Pit cover

The manure pit was covered to control the initial conditions in the nursery room prior to pit-safety ventilation during the experiment. A 0.1 mm (4 mil) thick plastic cover was placed on top of the floor grating to prevent H₂S gas from entering the room airspace during manure pit agitation.

Several 50 mm × 100 mm (2 in. × 4 in.) wooden boards, oriented on-edge, were placed on the concrete floor adjacent to the floor grating. Masking tape was used to seal the gap between the boards and the grating.

Five 0.3 m (12 in.) wide heavy weight felt strips were placed on top of the floor grating under the steel pen divider fencing (Figure 3.17). The felt strips were carefully cut to fit around
obstructions such as vertical fence posts and prevent gas leaks during manure agitation (Figure 3.18).

![Image](image1.png)

**Figure 3.17.** Felt strips located under steel pen dividers.

![Image](image2.png)

**Figure 3.18.** Felt strips cut to fit around pen fence supports.

The plastic sheeting was cut into six sections with an approximate width of 1.8 m (6 ft), with each section covering the floor grating in a single pen. The edges of the plastic sheeting
were placed so they overlapped the felt strips, thus preventing gas from escaping into the room during manure agitation.

The plastic sheets were sliced where necessary to allow them to be removed around obstructions including the vertical pit-safety ventilation fan discharge pipe (Figure 3.19) and gas meters located above the floor grating that could not be attached to pen fencing.

![Image of plastic cover split to fit around vertical pit-safety ventilation fan discharge pipe.](image)

Figure 3.19. Plastic cover split to fit around vertical pit-safety ventilation fan discharge pipe.

### 3.2.10 Motorized cover removal mechanism

The plastic cover was rolled up during removal from the floor using a motorized cover reel. The cover reel consisted of a sectional pipe shaft supported by bearings, and was driven by a gear reducer powered by a cordless drill operated at its slowest speed setting. The cover reel was used to eliminate the need for a person to enter the room to remove the cover after pit agitation, thus avoiding a safety hazard, and also minimizing air disturbances in the room caused by pulling the plastic away too quickly or at an uneven rate.
The cover take-up reel was constructed using 89 mm OD (3 in. nominal dia.) SCH. 40 PVC pipe sections. The pipe sections were fitted with wooden bushings and coupled using bolts that extended through the pipe, bushings, and wooden coupling shafts. The 76 mm OD × 32 mm ID (3 in. OD × 1-1/4 in. ID) pipe bushings were cut from 38 mm (1.5 in.) thick wooden blocks. Coupling shafts were constructed from 32 mm (1-1/4 in.) diameter wooden rods cut to 152 mm (6 in.) lengths. Coupling bolt holes with a diameter of 6.35 mm (0.25 in.) were drilled through the pipe, bushings, and coupling shafts, and the assembly was coupled using 6.35 mm diameter × 101.6 mm (1/4 in.-20 × 4 in.) long bolts, with double nuts used for thread locking.

Pillow block bearings were used to support the pipe shafts at the center and both ends of the room. The bearings were mounted to 89 mm × 140 mm (4 in. × 6 in. nominal) wooden block spacers so that the top of the pipe shaft was approximately the same height as the top of the floor grating. This arrangement allowed the plastic cover to slide flat against the floor grating while being removed. Intermediate pipe shaft supports were constructed using 51 mm (2 in.) diameter caster wheels mounted upside-down to 51 mm × 102 mm (2 in. × 4 in.) wooden blocks. The plastic cover sections were laid in place on the floor grating within each pen and affixed to the pipe shaft using heavy duty duct tape. Figure 3.20 shows the assembled cover reel.
A right-angle gear reducer with a 9.3:1 ratio was mounted to a 41 mm × 41 mm (1-5/8” × 1-5/8”) slotted steel strut channel and connected to a wooden drive shaft that extended outside of the nursery room through the entry doorway. The gearbox was powered by a DeWALT Model DCD951KL cordless drill operated at 500 rpm (Figure 3.21). The cover reel rotated at 53.6
RPM, resulting in a linear cover removal speed of 0.25 m/s (0.82 ft/s). The time required to remove the 2.7 m (9 ft.) long cover was approximately 11 seconds.

Figure 3.21. Cordless drill and right-angle gear reducer used to remove the plastic cover.

3.2.11 Manure pit agitators

The manure pit was agitated using two detachable blowers from Craftsman wet/dry vacuum cleaners (P/N 113.170250). The blowers were attached by a 50 mm (2 in.) diameter corrugated plastic hose to 50 mm (2 in.) SCH. 40 PVC pipe manifolds (Figure 3.22). The pipe manifolds divided air flow into four distribution pipes that were 0.91 m (36 in.) long and capped at one end. The end caps had one 12.7 mm (½ in.) diameter hole drilled through the center, and the distribution pipes had four 12.7 mm (½ in.) diameter holes (spaced 0.25 m (10 in.) on-center)
drilled through both sides. Each blower supplied air at a flow rate of approximately 0.08 m³/s (172 cfm).

Air was discharged horizontally along the pit floor to prevent excessive manure surface splashing. The manifold pipes were placed on the floor of the manure pit on either side of the 0.41 m (16 in.) high divider wall (Figure 3.23).
The two blowers used to supply air to the manifold were hung from the top rail of the pen divider fencing. One section of floor grating was replaced by a rectangular wooden plate with holes for the manifold pipe stubs to pass through, and the blower air supply hoses were connected to the manifold pipe stubs using hose clamps (Figure 3.24). The blowers were controlled remotely from a circuit breaker located outside of the nursery room.
3.2.12 Experiment gas monitor locations

A larger number of gas monitors was used for the ventilation experiment performed in Nursery Room #3 to capture more data spatially. A total of eleven MX6 meters were used. Since the MX6 meters record measurements every second, seven of these meters were located 0.15 m (6 in.) above the floor, which was the plane of most interest in this study. Four Tango TX1 meters and two MX6 meters were placed 0.30 m (12 in.) below the floor grating inside the manure pit to record pit concentration. The remaining two MX6 meters were used to record measurements 0.61 m (24 in.) above the floor in the corners of the room where gas pockets were expected as a result of the preliminary CFD simulation and observed during the trial run. The spatial locations of the meters are listed in Table 3.4 (with respect to the origin (0,0) shown in Figure 3.25).
Table 3.4. Experiment Gas Monitor Location Details.

<table>
<thead>
<tr>
<th>Height* m (ft)</th>
<th>Meter</th>
<th>X m (ft)</th>
<th>Y m (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.30 m (-12 in.)</td>
<td>MX6-1</td>
<td>10.79 m (35.40 ft)</td>
<td>0.61 m (2.00 ft)</td>
</tr>
<tr>
<td></td>
<td>MX6-2</td>
<td>0.30 m (1.00 ft)</td>
<td>0.61 m (2.00 ft)</td>
</tr>
<tr>
<td></td>
<td>TX1-1</td>
<td>7.38 m (24.20 ft)</td>
<td>2.51 m (8.22 ft)</td>
</tr>
<tr>
<td></td>
<td>TX1-3</td>
<td>5.55 m (18.20 ft)</td>
<td>2.51 m (8.22 ft)</td>
</tr>
<tr>
<td></td>
<td>TX1-2</td>
<td>3.72 m (12.20 ft)</td>
<td>2.51 m (8.22 ft)</td>
</tr>
<tr>
<td></td>
<td>TX1-4</td>
<td>1.89 m (6.20 ft)</td>
<td>2.51 m (8.22 ft)</td>
</tr>
<tr>
<td>+0.15 m (+6 in.)</td>
<td>MX6-5</td>
<td>9.24 m (30.30 ft)</td>
<td>0.61 m (2.00 ft)</td>
</tr>
<tr>
<td></td>
<td>MX6-6</td>
<td>9.24 m (30.30 ft)</td>
<td>2.46 m (8.08 ft)</td>
</tr>
<tr>
<td></td>
<td>MX6-7</td>
<td>5.58 m (18.30 ft)</td>
<td>2.16 m (7.08 ft)</td>
</tr>
<tr>
<td></td>
<td>MX6-8</td>
<td>5.58 m (18.30 ft)</td>
<td>2.46 m (8.08 ft)</td>
</tr>
<tr>
<td></td>
<td>MX6-9</td>
<td>1.92 m (6.30 ft)</td>
<td>0.30 m (1.00 ft)</td>
</tr>
<tr>
<td></td>
<td>MX6-10</td>
<td>1.92 m (6.30 ft)</td>
<td>2.46 m (8.08 ft)</td>
</tr>
<tr>
<td></td>
<td>MX6-11</td>
<td>1.22 m (4.00 ft)</td>
<td>1.22 m (4.00 ft)</td>
</tr>
<tr>
<td>+0.61 m (+24 in.)</td>
<td>MX6-3</td>
<td>10.79 m (35.40 ft)</td>
<td>0.61 m (2.00 ft)</td>
</tr>
<tr>
<td></td>
<td>MX6-4</td>
<td>0.30 m (1.00 ft)</td>
<td>0.61 m (2.00 ft)</td>
</tr>
</tbody>
</table>

*Vertical height with respect to top elevation of floor grating (positive direction upward)

Data were recorded using eleven Industrial Scientific MX6 iBrid multi-gas meters, and four Tango TX1 single-gas meters. The meters were turned on, then carefully placed according to the schematics shown in Figure 3.25, Figure 3.26, and Figure 3.27.
Figure 3.25. Schematic showing gas measurement locations 0.30 m (12 in.) below the floor.

Figure 3.26. Schematic showing gas measurement locations 0.15 m (6 in.) above the floor.
Figure 3.27. Schematic showing gas measurement locations 0.61 m (24 in.) above the floor.

Four Tango TX1 meters were placed below the floor grating to monitor manure pit concentrations during the experiment (Figure 3.28). The Tango TX1 gas monitors were hung below the floor grating using nylon wire ties adjusted so that the centerline of the measurement sensor inlet was 0.30 m (12 in.) below the top of the flooring (Figure 3.29). The M40-Window gas monitor was taped in place 0.91 m (36 in.) above the floor with the display visible through the room window (Figure 3.30).
Figure 3.28. Photo showing gas monitor placement 0.30 m (12 in) below the floor.

Figure 3.29. Tango TX1 meter suspended 0.30 m (12 in.) below floor.
The MX6 iBrid gas monitors located 0.15 m (6 in.) above the floor grating were placed on wooden blocks so that the sensor arrays were centered about the measuring plane regardless of meter orientation (vertical or horizontal). They were held against the pen divider fencing with a velcro strap. These meters included MX6-5, MX6-6, MX6-7, and MX6-8 (Figure 3.30), and MX6-9 and MX6-10 (Figure 3.31). Meters MX6-7, MX6-8, and MX6-10 had sampling pumps installed without tubing, and were mounted horizontally to place the sampling port inlet 0.15 m (6 in.) above the floor grating. Meter MX6-11 was placed vertically on a flat wooden block on top of the floor grating, and was held in place using tape to prevent it from being dislocated during pit cover removal (Figure 3.31).

![Figure 3.30. Photo showing gas monitor placement in selected locations.](image)
The MX6 iBrid gas monitors located 0.61 m (24 in.) above the floor were supported using metal lab clamps and stands. The MX6 iBrid gas monitors that used sampling pumps to monitor gas concentrations below the floor (MX6-1 and MX6-2) were also supported on the test stands, and sampling tubes were lowered 0.30 m (12 in.) through the floor grating and taped to metal brazing rods to keep the tubing straight and in the correct position during the experiment (Figure 3.32).

Figure 3.31. Photo showing gas monitors placed on wooden blocks.

Figure 3.32. Photo showing gas monitors supported by lab test stands.
3.2.13 Nursery room protocols

The following nursery room and pit-safety ventilation protocols were followed for all subsequent nursery room experiments:

1. All animals were removed from the nursery room prior to performing the experiment.
2. The manure depth was 0.43 m (17 in.). The manure surface was 25.4 mm (1 in.) above the top of the pit divider wall.
3. All feeders were removed from the room.
4. The room heaters were turned off.
5. Only the small barn fan (EF7) was used to ventilate the nursery room.
6. The meters were turned on during equipment setup and logged data continuously until the end of the experiment.

3.2.14 Modified measurement procedure for main experiment

The pit-safety ventilation fan was located outside of the room, with the door open just wide enough (approximately 0.2 m (8 in.)) that the fan outlet hose could be ducted to the manure pit. The door opening was sealed to prevent air leaks using plastic sheeting and masking tape. The pit-safety ventilation fan was controlled manually from a switch located on the fan power cord. The nursery room exhaust fan and agitation blowers were controlled from circuit breakers located outside of the nursery room. The following were key initial conditions and procedures followed for each experimental run:

1. The initial H₂S concentration was less than 1 ppm everywhere inside the room.
2. Room exhaust fan and pit-safety ventilation fan were turned OFF.
3. Manure pit was covered.
4. Negative-pressure pit fan outlet was uncovered (removed tape to expose hole).
5. The pit agitation blowers were turned ON (Breaker #10) to agitate the manure in the pit and generate H₂S gas in the manure pit. The agitation blowers were run for 2 minutes.

6. The pit agitation blowers were turned OFF (Breaker #10).

7. The room exhaust fan (EF7) was turned ON (Breaker #28) and run for 30 seconds to remove any gases that may have escaped from the pit during agitation.

8. Negative-pressure pit fan outlet was covered (with tape).

9. With all fans OFF, the manure pit was uncovered.

10. Simultaneously turned the room exhaust fan (EF7) and the pit-safety ventilation fan ON (Breaker #28 and Pit-safety fan Switch on power cord).

11. The room exhaust fan (EF7) and the pit-safety ventilation fan were run continuously until all alarms were silent, which occurred within 5 minutes.

12. The room exhaust fan (EF7) and the pit-safety ventilation fan were run for an additional 5 minutes to allow the gas levels inside the room to return to less than 1 ppm.
3.2.15 Experiment time schedule

The ventilation experiment was performed on September 23, 2014. The actual sequence of events for the four replications performed during the experiment is shown in Table 3.5.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time of Day, PM (hh:mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rep 1</td>
</tr>
<tr>
<td>Start agitation</td>
<td>5:06</td>
</tr>
<tr>
<td>Stop agitation</td>
<td>5:08</td>
</tr>
<tr>
<td>Start Room Fan</td>
<td>5:08</td>
</tr>
<tr>
<td>Stop Room Fan</td>
<td>5:09</td>
</tr>
<tr>
<td>Cover Hole</td>
<td>5:09</td>
</tr>
<tr>
<td>Uncover Pit</td>
<td>5:09</td>
</tr>
<tr>
<td>Start All Fans(^1)</td>
<td>5:10</td>
</tr>
<tr>
<td>Stop All Fans(^1)</td>
<td>5:20</td>
</tr>
<tr>
<td>Duration</td>
<td>0:14</td>
</tr>
</tbody>
</table>

\(^1\) Positive pressure pit-safety fan and negative pressure nursery room fan (EF7).
3.3 Results and discussion

This section describes the post-processing procedures used to format the recorded data from the gas monitors and presents the measured data set.

3.3.1 Data analysis procedure

The following post-processing protocols were followed for all measured experimental data.

1. The data log for each meter was downloaded. The time and H₂S concentration columns for each meter were copied into an Excel spreadsheet that contained the measured data for all meters.

2. This Excel file contained one column for each meter. That column had all of the measured data for the entire day. Four replications were recorded during the afternoon with only the small barn fan operating. Figure 3.33 shows the entire recorded dataset from the experiment in graphical format.
Figure 3.33. Graph showing measured concentration vs. time data from full experiment.

3. Each replication was identified using the recorded starting and ending times from the experiment. The starting time for ventilation was used as time = 0 for each replication, and the four replications were plotted on the same graph. This was done so the data could be compared to results from CFD simulation of only the ventilation event.

4. Each meter had its own datalogger, and the date and time were not synchronized between meters. For this reason, measures were taken to apply a time shift value for each meter and the starting time for each replication so that the replications were aligned correctly in time.
5. The measured values for each meter from all four replications were averaged, and upper and lower boundaries representing ± 2 standard deviations (SD) were calculated (95% CI).

3.3.2 Measured data set

This section describes the measured data set for the swine nursery room study. The measured data shows the behavior of H$_2$S gas as it is being evacuated from the manure pit and into the barn airspace during simultaneous pit and barn ventilation. Figures 3.37 to 3.49 show graphs of the average (± 2 SD) measured H$_2$S gas concentration at each meter location during the first five minutes of pit and barn ventilation for all four replications. The graphs are presented in separate subsections for meters located 0.30 m (12 in.) below, 0.15 m (6 in.) above, and 0.61 m (24 in.) above the floor grating.

3.3.2.1 Pit-safety fan inlet concentration

Two additional gas meters were used to monitor the H$_2$S gas concentration of the incoming ventilation air. One M40 meter was placed under the inlet of the pit-safety ventilation fan (Figure 3.34), and a Ventis MX4 meter was attached to a short section of vinyl tubing that extended through the room doorway and was inserted through the vertical PVC discharge pipe 1.22 m (48 in.) above the floor (Figure 3.35). The meter located at the inlet of the pit-safety ventilation fan measured zero concentration of H$_2$S gas for the entire duration of the experiment, which confirms that fresh air was supplied to the manure pit during ventilation. The Ventis MX4 meter used to monitor the gas concentration in the vertical discharge pipe measured a zero H$_2$S concentration at all times except during pit agitation, when a maximum reading of 6 ppm was recorded prior to the start of pit-safety ventilation. This indicates that only a very low quantity of gas was entering the vertical discharge pipe during manure agitation.
Figure 3.34. Pit-safety fan inlet gas concentration meter.

Figure 3.35. Pit-safety fan discharge pipe gas monitor tubing.
3.3.2.2 Hallway safety monitoring

One M40 meter was placed in the hallway, located in the center of the building (Figure 3.36). This meter was used to monitor gas levels in the swine building outside of Nursery Room #3 for safety purposes. This meter recorded a maximum concentration of H$_2$S gas of 0 ppm, indicating that no H$_2$S gas escaped from the nursery room into the hallway during the experiment.

Figure 3.36. Hallway M40 meter placement for safety purposes.
3.3.2.3 Meters located 0.30 m below the floor

Meters TX1-1, TX1-3, TX1-2, TX1-4, MX6-1, and MX6-2 measured H₂S gas concentrations in the manure pit, 0.30 m (12 in.) below the floor grating. The initial manure pit concentration was the lowest near the pit-safety ventilation fan inlet, and highest near the barn exhaust fan. The average measured initial concentration inside the manure pit was 76 ppm, with a range of 27 to 125 ppm. Figures 3.37 to 3.42 show the H₂S gas concentration inside the manure pit decayed rapidly during the first 300 s (5 min.) of ventilation.
Figure 3.37. Average (± 2 SD) measured H₂S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-1, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 3.38. Average (± 2 SD) measured H₂S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-3, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 3.39. Average (± 2 SD) measured H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-2, 0.30 m (12 in.) below the floor grating.  
(Inset plan view image of nursery room shows meter location)

Figure 3.40. Average (± 2 SD) measured H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-4, 0.30 m (12 in.) below the floor grating.  
(Inset plan view image of nursery room shows meter location)
Figure 3.41. Average (± 2 SD) measured H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-1, 0.30 m (12 in.) below the floor grating. (Inset plan view image of nursery room shows meter location)

Figure 3.42. Average (± 2 SD) measured H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-2, 0.30 m (12 in.) below the floor grating. (Inset plan view image of nursery room shows meter location)
3.3.2.4 Meters located 0.15 m above the floor

Meters MX6-5 to MX6-11 measured H$_2$S gas concentrations in the nursery room airspace, 0.15 m (6 in.) above the floor grating. Figures 3.43 to 3.49 show that the initial H$_2$S gas concentration started at or near zero, rose to a maximum level, ranging from 4 ppm for meter MX6-6 to 103 ppm for meter MX6-10, then decayed back to near zero as the gas was exhausted from the barn airspace during ventilation.

Meter MX6-6 was the closest meter to the pit-safety ventilation fan inlet and recorded the lowest H$_2$S gas concentration after ventilation started (4 ppm when t = 40 s). Meter MX6-10 recorded the highest H$_2$S gas concentration after ventilation started (103 ppm when t = 34 s). MX6-10 was located directly above meter TX1-4 and downwind of meter TX1-2, which were located inside the manure pit and had the highest initial H$_2$S gas concentrations (119 and 125 ppm, respectively).

Meters MX6-7 and MX6-8 were located at the center of the room spaced only 0.30 m (12 in.) apart to capture small spatial differences in concentration of the gas cloud moving through the room. Figure 3.46 clearly shows that meter MX6-8 recorded a higher peak H$_2$S concentration (33 ppm when t = 25 s) than meter MX6-7 (Figure 3.45), which showed two lower peaks (24 ppm when t = 20 s, and 23 ppm when t = 56 s) separated by a short (36 s) duration of time.
Figure 3.43. Average (± 2 SD) measured H\textsubscript{2}S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-5, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 3.44. Average (± 2 SD) measured H\textsubscript{2}S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-6, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 3.45. Average (± 2 SD) measured H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-7, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 3.46. Average (± 2 SD) measured H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-8, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 3.47. Average (± 2 SD) measured H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-9, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 3.48. Average (± 2 SD) measured H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-10, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 3.49. Average ($\pm$ 2 SD) measured H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-11, 0.15 m (6 in.) above the floor grating. (Inset plan view image of nursery room shows meter location)

### 3.3.2.5 Meters located 0.61 m above the floor

Meters MX6-3 and MX6-4 measured H$_2$S gas concentrations in the nursery room airspace, 0.61 m (24 in.) above the floor grating. Figure 3.50 shows the gas decay curve for meter MX6-3, which was located in the corner of the nursery room near the pit-safety ventilation fan inlet and recorded a maximum H$_2$S gas concentration of 10 ppm when $t = 17$ s after the start of pit and barn ventilation. Figure 3.51 shows rapid variation in measured gas concentration at meter location MX6-4. This suggests a region with a high velocity gradient, probably due to close proximity to the small barn fan. Meter MX6-4 recorded a maximum H$_2$S gas concentration of 24 ppm when $t = 80$ s after the start of pit and barn ventilation.
Figure 3.50. Average (± 2 SD) measured H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-3, 0.61 m (24 in.) above the floor grating. 
(Inset plan view image of nursery room shows meter location)

Figure 3.51. Average (± 2 SD) measured H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-4, 0.61 m (24 in.) above the floor grating. 
(Inset plan view image of nursery room shows meter location)
3.4 Summary of observations

After the experiment, it was determined that the initial gas concentrations inside the manure pit prior to ventilation were non-uniform. Several factors may have contributed:

1. Possible leakage of gas from beneath the floor during agitation where the plastic sheeting that covered the floor grating overlapped the felt strips below pen fencing or where the sheeting was split to fit around obstructions such agitator hoses, pit-safety fan ducting, and instruments with floor supports at measurement locations MX6-3, MX6-4, and MX6-11.

2. Possible diffusion of gas from beneath the floor during the period of time when the plastic sheeting was removed from the floor after agitation and just prior to the start of ventilation.

3. The manure pit was divided by a wall, and one half of the agitation manifold became, at least partially, plugged with solids prior to the experiment, so only one half of the manure pit was fully agitated and released H₂S gas.
Chapter 4

Phase I CFD Simulations and Validation

4.1 Introduction

A Computational Fluid Dynamics (CFD) model of the swine nursery room was created using SolidWorks Flow Simulation (SWFS). Simulations were performed to show that SWFS is a suitable CFD tool that can be used to simulate hydrogen sulfide (H$_2$S) gas evacuation from ventilated manure pits located beneath mechanically ventilated barns. The CFD model was validated using measured gas decay data obtained from the experiments described and performed in Chapter 3.

4.2 Methodology

This section describes the CFD model that was developed to simulate ventilation of the nursery room with assumptions and simplifications. First, the CFD model is described. The initial and boundary conditions for the model are also described in detail. Suitable grid and time step sizes were identified by conducting grid and time step size studies.
4.3 Nursery room CFD model

SolidWorks Flow Simulation 2015 was used to create a CFD model for the nursery room and perform transient CFD simulations. This section describes how room features were represented in the CFD model. Figure 4.1 is a schematic for the CFD model of the nursery room.

Two heaters suspended from the nursery room ceiling were included in the CFD model as solid obstructions to air flow. The fluorescent lighting located at the center of the room width was not included in the model because it had a low profile and did not restrict airflow.
The vertical pit-safety ventilation fan discharge pipe, ducting elbow, and fan duct were included in the CFD model as solid obstructions to air flow. The pen divider fencing was not included in the CFD model because it was not expected to create a large enough resistance to air flow to justify the refinements needed to capture the small solid features in the mesh.

The divider wall in the manure pit was not included in the model because the wall was submerged below the manure level when the experiment was performed. The manure surface was represented by a solid object which defined the lower boundary of the computational domain.

4.3.1 General CFD model settings

This section describes the general settings used in SWFS for the CFD model of the nursery room. The transient simulation had a total duration of 300 s (5 min) to match the duration of the main ventilation event during the experiment. Gravity was set to -9.8 m/s² (-32.2 ft/s²). Standard temperature and pressure were specified for ambient conditions (20.0°C (68°F) and 101.3 kPa (14.7 psi), respectively). Appendix B lists the specific CFD model settings used for the simulations.

4.3.2 Turbulence model parameters

The initial conditions prior to turning on the pit and barn fans were quiescent (still air). Since values of zero were not allowed by the software, the initial parameters for turbulence intensity (I) and length (l) used in the k-ε turbulence model were set nearly equal to zero (I = 1 × 10⁻⁶ % and l = 2.54 × 10⁻⁸ m (1 × 10⁻⁶ in.), respectively). These values were used for initial conditions for the room airspace and environmental pressure openings. For the pit-safety ventilation fan, the initial turbulence values were set equal to I = 5% and l = 36.32 mm (1.43 in., the value set by SWFS as a default for the selected geometry).
4.3.3 Gas concentrations

The only fluids in the computational domain were air (using the default fluid definition in SWFS) and hydrogen sulfide gas. Initial concentrations were specified using the volume fraction (ppm) of each gas. Initially, only air with a concentration of 1,000,000 ppm was specified everywhere in the nursery room airspace above the floor grating. This value was also used for air entering from environmental pressure openings and the ducted pit-safety ventilation fan. Hydrogen sulfide gas was only specified as an initial concentration inside the manure pit, with the remainder of the total concentration by volume consisting of air.

4.3.4 Goals and convergence criteria

Because the simulation was transient, convergence criteria, called goals in SWFS, were only used to track the values of solution variables during the calculations. Global average values for pressure, turbulent energy, turbulent dissipation, velocity (magnitude, in the X, Y, and Z directions), and mass of fluid were saved at each 1 second interval of the simulation. The global average and maximum volume fraction of hydrogen sulfide gas were also saved. Point parameters were used to track H$_2$S concentrations at each of the gas meter locations used during the ventilation experiment described in Table 3.4 on page 57.

4.3.5 Boundary conditions

Boundary conditions and model parameters were based on measured values wherever possible. The interior of the nursery room was modeled with adiabatic smooth surfaces with a roughness height of 0 µm (0 µin.).
4.3.5.1 Pit and barn ventilation fans

Measured, inlet and outlet velocity boundary conditions were used to represent the pit and barn ventilation fans. The average measured pit-safety fan inlet velocity was 6.11 m/s (20.05 ft/s). A local initial mesh refinement level of two was applied to the fan inlet surface to divide the mesh at that location into smaller rectangles to more accurately capture the integrated surface area of the circular inlet (m² (ft²)) which determined the air flow rate used in calculations (Q = V×A). This was necessary because the modeled pit-safety fan inlet surface was represented by simplified geometry defined by a circle drawn on a flat plate. The average measured barn fan outlet velocity was 5.77 m/s (18.92 ft/s). The outlet velocity boundary condition was applied to the face of a solid lid that covered the entire outside wall of the nursery room. The barn fan opening through the outside wall, together with the prescribed velocity, controlled the volumetric flow rate of air leaving the nursery room (Q = V×A) that did not require mesh refinement.

4.3.5.2 Nursery room ceiling

The ceiling of the nursery room was constructed of perforated corrugated sheet metal, with 12.7 mm (½ in.) diameter holes located equally across the ceiling on 0.15 m × 50.8 mm (6 in. × 2 in.) center spacing. Perforated plates can be defined in SWFS by specifying the hole diameter and pitch (spacing) in the X and Y directions, so the ceiling was represented by a perforated plate placed over an environmental pressure boundary condition.

4.3.5.3 Air inlet curtain

The opening beneath the air inlet curtain located above the room doorway was 6.35 mm (0.25 in.) high during operation of the small barn fan and the pit-safety ventilation fan. The average measured inlet velocity below the curtain was 0.92 m/s (181 ft/min) along the X axis
(parallel to the length of the room). The equivalent curtain inlet air flow rate, calculated from the
curtain opening dimensions and the measured air velocity, was 0.021 m$^3$/s (45 cfm). That
represented only 3.3% of the total air flow through the room, so the inlet curtain opening was
modeled as a solid object without flow in this simulation.

4.3.6 Porous media used to represent swine floor grating

The flooring in the nursery room consisted of interlocking sections of molded
polypropylene swine floor grating. One section of swine floor grating measures 0.61 m long ×
0.46 m wide (24 in. long × 18 in. wide), and has a thickness of 9.53 mm (3/8 in.). The grating has
42.4% open area, with diagonal rounded slots with approximate dimensions of 87.31 mm long ×
11.11 mm wide (3-7/16 in. long × 7/16 in. wide) (Figure 4.2).

![Figure 4.2. One section of swine floor grating used in the nursery room.](image)

It was assumed that the grating acts as a uniform resistance to air flow. To avoid an
unnecessarily dense mesh in the region of the floor grating, a porous medium was defined with
the same flow characteristics, i.e. pressure drop, as the grating. The floor grating was simulated
in a modeled wind tunnel (Figure 4.3) with ideal (frictionless) walls, so that the only resistance to
flow was due to the grating itself.
Figure 4.3. Swine floor grating placed in a modeled wind tunnel.

The grating was placed at the center of the wind tunnel length. The tunnel extended for a length of 2.44 m (8 ft) on both sides of the grating. One end of the tunnel had an inlet volume flow rate boundary condition, and the other end was defined as an opening at environmental pressure. A steady-state parametric study was performed to determine the pressure drop across the grating over a range of air flow rates from 0.02 to 0.47 m$^3$/s (50 to 1,000 cfm). The pressure drop was defined as the difference in pressure between the top and bottom surfaces of the grating. In general, the pressure drop across the floor grating varied with air velocity squared. Equations 4-1 and 4-2 show this relationship in Metric and English units.

\[
\Delta P (\text{Pa}) = 6.49 \times [V (\text{m/s})]^2 \\
\Delta P (\text{psi}) = 2.40 \times 10^{-8} \times [V (\text{ft/min})]^2
\]

Where: \(\Delta P\) = pressure drop, Pa (psi)

\(V\) = velocity, m/s (ft/min)
The nursery room floor grating was 9.53 mm (3/8 in.) thick, which would have resulted in an unnecessarily fine mesh through the flooring. To simplify the model so that a coarser mesh could be used, the porous media was defined with a thickness of 50.8 mm (2 in.). A unidirectional porous medium was created using the pressure drop vs. flow rate values from simulations using the modeled swine floor grating geometry, and the grating in the simulation was replaced with the porous medium. The simulation cases were then repeated to verify that the porous medium created an equivalent resistance to flow. The resulting pressure drop across the porous medium was within 2.91% of the values obtained using the floor grating geometry for the lowest flow rate used, and within 0.30% for all other flow rates (Table 4.1).

<table>
<thead>
<tr>
<th>Q (m³/s)</th>
<th>Grating Pressure Drop (Pa)</th>
<th>Porous Media Pressure Drop (Pa)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.05</td>
<td>0.05</td>
<td>2.91</td>
</tr>
<tr>
<td>0.05</td>
<td>0.20</td>
<td>0.20</td>
<td>0.00</td>
</tr>
<tr>
<td>0.07</td>
<td>0.44</td>
<td>0.44</td>
<td>0.00</td>
</tr>
<tr>
<td>0.09</td>
<td>0.77</td>
<td>0.77</td>
<td>0.00</td>
</tr>
<tr>
<td>0.12</td>
<td>1.20</td>
<td>1.20</td>
<td>0.00</td>
</tr>
<tr>
<td>0.14</td>
<td>1.71</td>
<td>1.71</td>
<td>0.00</td>
</tr>
<tr>
<td>0.19</td>
<td>3.02</td>
<td>3.01</td>
<td>0.23</td>
</tr>
<tr>
<td>0.24</td>
<td>4.68</td>
<td>4.67</td>
<td>0.15</td>
</tr>
<tr>
<td>0.28</td>
<td>6.71</td>
<td>6.69</td>
<td>0.21</td>
</tr>
<tr>
<td>0.35</td>
<td>10.42</td>
<td>10.40</td>
<td>0.13</td>
</tr>
<tr>
<td>0.47</td>
<td>18.40</td>
<td>18.35</td>
<td>0.30</td>
</tr>
</tbody>
</table>

To further simplify the CFD model, the six felt strips that were placed under the pen divider fencing during the ventilation experiment were modeled as 50.8 mm (2 in.) thick solids between sections of porous media. The pit-safety fan discharge pipe mounting plate and agitation
manifold hose plate were also modeled as 50.8 mm (2 in.) thick solids to replace removed sections of floor grating (Figure 4.4).

Figure 4.4. Plan view of nursery room floor showing locations of porous media regions, felt strips, pit-safety fan discharge pipe plate, and agitation manifold plate.
4.3.7 Phase I grid convergence study

A grid convergence study was performed to quantify the level of uncertainty in the simulation coming from the discretized computational grid. The typical procedure is to select a level of error that is deemed acceptable, then perform steady-state simulations at each candidate mesh size until the value of the variable of interest changes by less than the selected error level between subsequent mesh refinements. The tradeoff between error level and mesh refinements is computational time which increases as the mesh gets further refined.

The instruments used for the physical experiment in the nursery room have a measurement accuracy of ±15% over the full ranges of environmental operating temperature and humidity. This was considered when selecting the level of acceptable error of 5% for this grid dependency study, along with the increase in computational time for denser meshes.

SWFS uses Cartesian meshing with cuboid shaped cells. The candidate meshes divided the computational domain into a number of cells of equal length in the X, Y, and Z directions, denoted \( N_x, N_y, \) and \( N_z \), respectively. A mesh refinement factor of 1.2 was used to increase the number of cells in each direction for successive cases. Because the pit-safety ventilation fan discharge pipe was located inside of the computational domain instead of at a boundary, a local mesh refinement level of 2 was used at the fan outlet surface to more accurately capture the full surface area. Table 4.2 shows the candidate mesh levels used for the grid convergence study.
Table 4.2. Candidate mesh levels used for Phase I grid convergence study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cells $(N_x,N_y,N_z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100,40,32</td>
</tr>
<tr>
<td>2</td>
<td>120,48,39</td>
</tr>
<tr>
<td>3</td>
<td>144,58,46</td>
</tr>
<tr>
<td>4</td>
<td>172,70,55</td>
</tr>
<tr>
<td>5</td>
<td>206,84,65</td>
</tr>
<tr>
<td>6</td>
<td>248,100,79</td>
</tr>
</tbody>
</table>

Grid convergence studies are sometimes performed using steady-state calculations. However, for unsteady flows this presents a problem since the flow pattern may change at different time moments. A steady-state study was attempted, using velocity as the convergence criteria at points that did not change during mesh refinements (intersections of control planes). However, it was discovered that this problem deals with unsteady flows, and a stable velocity profile was not achieved even after many iterations at any mesh level.

One method of dealing with unsteady flows is to use a transient solver, then assess the level of convergence after a set number of total calculation iterations. However, SWFS does not allow access to the number of iterations per time step (dictated by the internal convergence criteria in the software), and the solver changed the number of internal iterations automatically for different grid levels, which made it impossible to make valid comparisons from one mesh level to the next. Overall, the simulation results did not converge monotonically, which made it impossible to use typical grid convergence assessment techniques.

Since the variable of interest was the integral concentration of H$_2$S gas in the computational domain during the first 300 seconds (5 min) of ventilation, the global average (Global $C_{avg}$) volume fraction of H$_2$S gas was used to establish grid convergence. Transient simulations were performed using a 1.0 second time step size. The area under the $C_{avg}$ vs. time...
curve was integrated using the trapezoid rule, and the integral values were compared to determine the percent difference between subsequent mesh levels. The integrated maximum (Planar $C_{\text{max}}$) and average (Planar $C_{\text{avg}}$) concentrations on the plane located 0.15 m (6 in.) above the floor grating were used to further assess grid convergence.

The integral differences between Case 1 and Case 2 (Table 4.3) were, respectively, 0.23%, 2.69%, and 4.93% for global average concentration, and maximum and average concentrations at the instrument measurement plane located 0.15 m (6 in.) above the slotted floor grating in the nursery room. The next refinement resulted in a difference of 7.24% in Planar $C_{\text{max}}$ between Case 2 and Case 3. Although there was still oscillation in convergence criteria as the grid was further refined beyond Case 3, the criteria all fell below the 5% limit for acceptable uncertainty. The integral differences between Case 3 and Case 4 were 0.79%, 1.51%, and 3.58% for global average concentration, and maximum and average concentrations. Simulations were performed for Case 3 with 144,58,46 cells at 1s and 0.5s time step sizes, but the resulting validation analysis had fewer meter locations that matched the measured data and fewer within $\pm 2$ S.D. of the average measured values when compared to Case 1 simulations with 100,40,32 cells and a time step size of 1s. The reason for this discrepancy was most likely due to the Courant number becoming higher as the mesh became finer – with each subsequent mesh refinement, in order to maintain a low Courant number, a smaller time step size is needed (for the same velocities in the computational domain). The result of this is that overall computation time becomes greatly increased with finer mesh and smaller time step sizes, and even a smaller time step size of 0.5s did not result in an improved match between the simulation and physical experiment.

Because the integral differences between Case 1 and Case 2 were lower than the acceptable error level of 5%, Case 1 was deemed suitable for use in the validation simulations for comparison to the experimentally measured data. Table 4.4 is a summary of the final grid
dimensions used for the nursery room CFD model. Figure 4.5 is a cross section of the nursery room showing the selected mesh.

Table 4.3. Difference (%) between subsequent mesh levels for Phase I grid convergence study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cells ((N_x,N_y,N_z))</th>
<th>Integrated Global (C_{avg})</th>
<th>Difference</th>
<th>Integrated Planar (C_{max})</th>
<th>Difference</th>
<th>Integrated Planar (C_{avg})</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100,40,32</td>
<td>1,300.0</td>
<td>-</td>
<td>11,962.2</td>
<td>-</td>
<td>2,705.8</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>120,48,39</td>
<td>1,297.1</td>
<td>0.23</td>
<td>11,644.9</td>
<td>2.69</td>
<td>2,575.7</td>
<td>4.93</td>
</tr>
<tr>
<td>3</td>
<td>144,58,46</td>
<td>1,285.2</td>
<td>0.92</td>
<td>12,520.0</td>
<td>7.24</td>
<td>2,575.5</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>172,70,55</td>
<td>1,295.4</td>
<td>0.79</td>
<td>12,710.4</td>
<td>1.51</td>
<td>2,484.9</td>
<td>3.58</td>
</tr>
<tr>
<td>5</td>
<td>206,84,65</td>
<td>1,278.0</td>
<td>1.35</td>
<td>13,161.3</td>
<td>3.49</td>
<td>2,512.5</td>
<td>1.11</td>
</tr>
<tr>
<td>6</td>
<td>248,100,79</td>
<td>1,274.6</td>
<td>0.27</td>
<td>12,691.7</td>
<td>3.63</td>
<td>2,458.8</td>
<td>2.16</td>
</tr>
</tbody>
</table>

Note: Difference (%) is a comparison between the current and previous value, where Difference (%) = \(\frac{|\text{Previous} - \text{Current}|}{\left(\frac{\text{Previous} + \text{Current}}{2}\right)} \times 100\)

Table 4.4. Final mesh dimensions used for the nursery room CFD model.

<table>
<thead>
<tr>
<th>(N_x)</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_y)</td>
<td>40</td>
</tr>
<tr>
<td>(N_z)</td>
<td>32</td>
</tr>
<tr>
<td>Total Cells</td>
<td>137,385</td>
</tr>
<tr>
<td>Fluid Cells</td>
<td>106,887</td>
</tr>
<tr>
<td>Solid Cells</td>
<td>8,119</td>
</tr>
<tr>
<td>Partial Cells</td>
<td>22,379</td>
</tr>
</tbody>
</table>
Figure 4.5. Final nursery room CFD model mesh with $100 \times 40 \times 32$ cells ($N_x \times N_y \times N_z$).
4.3.8 Phase I time step convergence study

A time step convergence study was performed to quantify the level of uncertainty coming from the size of the discretized time steps used to perform transient simulations. The selected Case 1 mesh was utilized, and transient simulations were performed using gradually smaller time step sizes (starting at 1s and decreasing by a factor of two) until the value of the variable of interest changed by less than the selected error level between subsequent refinements. The tradeoff between error level and time step size is computational time, which increases as the time step gets further reduced. Table 4.5 shows the candidate time step sizes used for the time step convergence study.

The instruments used for the physical experiment in the nursery room have a measurement accuracy of ±15% over the full ranges of environmental operating temperature and humidity. This was considered when selecting the level of acceptable error of 10% for this time step dependency study, as well as increases in computational time for smaller time steps.

Table 4.5. Candidate time step sizes used for the Phase I time step convergence study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Δt (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.125</td>
</tr>
</tbody>
</table>

The simulation results did not converge monotonically, so the same general procedure used for the grid dependency study was followed to quantify the level of uncertainty from the time step size used for transient simulations. The integral differences were 2.65%, 8.78%, and 0.61%, respectively, for global average concentration, and maximum and average concentrations.
at the instrument measurement plane located 0.15 m (6 in.) above the slotted floor grating in the nursery room (Table 4.6). These values were lower than the acceptable error level of 10%, therefore, a time step size of 1.0 second was deemed suitable for use in the validation simulations for comparison to the experimentally measured data.

Table 4.6. Difference (%) between subsequent time steps for the Phase I time step convergence study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Δt (s)</th>
<th>Integrated Global $C_{avg}$</th>
<th>Difference %</th>
<th>Integrated Planar $C_{max}$</th>
<th>Difference %</th>
<th>Integrated Planar $C_{avg}$</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>1,285.2</td>
<td>-</td>
<td>12,520.0</td>
<td>-</td>
<td>2,575.5</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1,251.6</td>
<td>2.65</td>
<td>13,669.5</td>
<td>8.78</td>
<td>2,591.2</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>1,232.8</td>
<td>1.51</td>
<td>13,878.1</td>
<td>1.51</td>
<td>2,487.2</td>
<td>4.09</td>
</tr>
<tr>
<td>4</td>
<td>0.125</td>
<td>1,221.3</td>
<td>0.94</td>
<td>13,493.5</td>
<td>2.81</td>
<td>2,411.5</td>
<td>3.09</td>
</tr>
</tbody>
</table>

Note: Difference (%) is a comparison between the current and previous value, where Difference (%) = [|Previous - Current| / [ (Previous + Current) / 2 ] ] * 100
4.4 Results

Simulations were performed using the CFD model developed for the nursery room using the identified suitable grid and time step sizes. The CFD model was validated by comparing simulation results to the measured data at each meter location in the manure pit and nursery room airspace using criteria given in section 4.4.2.

First, a simulation was run using a uniform initial concentration in the manure pit that was equal to the average measured initial concentration at each meter location 304.8 mm (12 in.) below the floor grating. This produced poor results however, since the initial H₂S concentration in the manure pit was non-uniform and varied spatially from 27 to 125 ppm.

Next, a bracketing study was performed to determine if simulations performed using uniform initial conditions in steps from the lowest to the highest measured initial concentration would “bracket” the actual solution at each meter location in the nursery room. It was observed that while no single uniform initial condition created a perfect match, the simulations run using the lowest or highest measured initial concentrations under or over predicted the concentrations at all meter locations inside the nursery room, respectively.

Last, simulations were performed using a variable initial concentration profile in the manure pit. The initial manure pit gas concentration profile was a linear function that assumed the pit airspace was divided equally by the longitudinal centerline of the manure pit. The initial manure pit gas concentration was assumed to be equal to the measured initial concentration at each meter location along the length of the manure pit, and the value varied linearly between meter locations. This concentration profile provided the best match for the measured data.

4.4.1 Comparing simulated results to measured values

Output from the CFD simulations was saved at 1 second intervals. This made it easy to compare the results with the measured data from the MX6 meters, which recorded measurements
at 1 second intervals. However, the TX1 meters took measurements every 2 seconds, and recorded an average value every 10 seconds. To make comparisons, the simulated results were averaged over a 10 second interval as follows:

1. The initial concentration was used as the starting value at time = 0 for each TX1 meter.
2. The simulated results for time = 1 to 10 seconds were averaged and stored in the Excel file for time = 10.
3. This was repeated until the end of the simulation (time = 300 seconds). So, the results for time = 11 to 20 seconds were averaged and stored for time = 20, 21 to 30 was averaged and stored for time = 30, and so on.

4.4.2 Validation criteria used

Validation criteria are used to quantify how well a CFD simulation models a physical system. Typical validation criteria specified for indoor ventilation simulations by ASTM D5157 are too strict for animal production facilities, where ambient and initial conditions are difficult to control precisely. Zhao (2006) used a set of relaxed statistical validation criteria that included the first three criteria from the ASTM D 5157-97 standard. A similar set of relaxed criteria was used to validate the CFD model for this study:

1. Regression of simulated vs. measured gas decay curve for each meter location.
   a. $0.75 < \text{Slope} < 1.25$
   b. $R^2$-squared value $> 0.80$ (*relaxed from 0.90)
   c. Intercept $< 27\%$ of the average measured concentration (*relaxed from 25%)
2. Percent of simulated values within 2 standard deviations of the average measured values $> 50\%$ (which corresponds to a 95% confidence interval). (*my addition)
A perfect match would result in a regression slope = 1, intercept = 0, $R^2 = 1.00$, and 100% of the values falling within 2 standard deviations of the average measured value.

### 4.4.3 Simulation using an average uniform initial concentration

The first simulation of the nursery room was performed using a uniform initial $\text{H}_2\text{S}$ concentration inside the manure pit equal to the average measured value from all meter locations inside the manure pit just prior to starting ventilation. The average value was 76 ppm, with a range of 27 to 125 ppm. The results of this simulation showed that using a uniform average initial concentration produced a poor match for the measured data at most meter locations, with only two meters inside the manure pit meeting all of the validation criteria (TX1-3 and TX1-4, in Table 4.7).

Figures 4.6 to 4.20 show the average measured (±2 S.D.) and simulated (for a uniform $C_0 = 76$ ppm) concentration vs. time at the meter locations. Generally, it appeared that the simulated gas decay curves closely resembled the measured data at several meter locations. A good example of this is at meter location MX6-7, which exhibits two peaks separated by a plateau prior to decay, and MX6-8, which exhibits a single peak before decay (shown in Figure 4.16 and Figure 4.17, respectively). These meters had been intentionally placed 0.30 m (12 in.) apart to test if the simulation could mimic small changes in spatial concentration as a cloud of gas passed over them during pit-safety ventilation.
Table 4.7. Statistical criteria for simulated vs. measured gas concentration data for the case with a uniform initial manure pit concentration of 76 ppm.

<table>
<thead>
<tr>
<th>Height(^a) m (ft)</th>
<th>Meter</th>
<th>Simulated vs. Measured Regression Statistics</th>
<th>Percent within 2 SD(^d)</th>
<th>27% of Average Measured Concentration(^f)</th>
<th># of Criteria Met(^g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Slope(^b)</td>
<td>Intercept(^c)</td>
<td>(R^2)</td>
<td></td>
</tr>
<tr>
<td>-0.30 m (-12 in.)</td>
<td>TX1-1</td>
<td>3.1680</td>
<td>-0.1825</td>
<td>0.9619</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>TX1-3</td>
<td>1.2491</td>
<td>-0.1658</td>
<td>0.9514</td>
<td>62.5</td>
</tr>
<tr>
<td></td>
<td>TX1-2</td>
<td>0.7671</td>
<td>-12.4567</td>
<td>0.8574</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>TX1-4</td>
<td>0.8321</td>
<td>1.3446</td>
<td>0.8125</td>
<td>68.8</td>
</tr>
<tr>
<td></td>
<td>MX6-1</td>
<td>1.4497</td>
<td>-2.5679</td>
<td>0.8922</td>
<td>90.7</td>
</tr>
<tr>
<td></td>
<td>MX6-2</td>
<td>1.3619</td>
<td>7.4020</td>
<td>0.8514</td>
<td>29.1</td>
</tr>
<tr>
<td>+0.61 m (+24 in.)</td>
<td>MX6-3</td>
<td>2.8463</td>
<td>7.1783</td>
<td>0.2419</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>MX6-4</td>
<td>2.1327</td>
<td>6.7121</td>
<td>0.5895</td>
<td>51.0</td>
</tr>
<tr>
<td>+0.15 m (+6 in.)</td>
<td>MX6-5</td>
<td>0.2638</td>
<td>22.8846</td>
<td>0.0548</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>MX6-6</td>
<td>-1.0306</td>
<td>4.9313</td>
<td>0.0448</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td>MX6-7</td>
<td>0.7078</td>
<td>19.5493</td>
<td>0.2327</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>MX6-8</td>
<td>0.7229</td>
<td>7.3040</td>
<td>0.6959</td>
<td>57.0</td>
</tr>
<tr>
<td></td>
<td>MX6-9</td>
<td>2.8460</td>
<td>20.8082</td>
<td>0.5459</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>MX6-10</td>
<td>0.3818</td>
<td>5.3217</td>
<td>0.8153</td>
<td>33.1</td>
</tr>
<tr>
<td></td>
<td>MX6-11</td>
<td>0.2611</td>
<td>27.8391</td>
<td>0.0406</td>
<td>37.8</td>
</tr>
</tbody>
</table>

a. Vertical height of meter \(\text{H}_2\text{S}\) sensor with respect to the top of the floor grating.
b. Slope from linear regression of simulated vs. measured \(\text{H}_2\text{S}\) gas concentration vs. time.
c. \(Y\)-intercept from linear regression of simulated vs. measured \(\text{H}_2\text{S}\) gas concentration vs. time.
d. \(R^2\) value from linear regression of simulated vs. measured \(\text{H}_2\text{S}\) gas concentration vs. time.
e. Percent of simulated values within ±2 S.D. of the average measured \(\text{H}_2\text{S}\) gas concentration vs. time.
f. \(0.27 \times\) the average measured \(\text{H}_2\text{S}\) concentration during the first 300s of pit and barn ventilation.
g. The total number of validation criteria met.
Figure 4.6. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) $\text{H}_2\text{S}$ gas concentration during the first 300s of pit and barn ventilation at meter location TX1-1, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.7. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) $\text{H}_2\text{S}$ gas concentration during the first 300s of pit and barn ventilation at meter location TX1-3, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.8. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-2, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.9. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-4, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.10. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-1, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.11. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-2, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.12. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-3, 0.61 m (24 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.13. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-4, 0.61 m (24 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.14. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-5, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.15. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-6, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.16. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-7, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.17. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-8, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.18. Average (± 2 SD) measured and simulated (uniform \( C_0 = 76 \) ppm) \( \text{H}_2\text{S} \) gas concentration during the first 300s of pit and barn ventilation at meter location MX6-9, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.19. Average (± 2 SD) measured and simulated (uniform \( C_0 = 76 \) ppm) \( \text{H}_2\text{S} \) gas concentration during the first 300s of pit and barn ventilation at meter location MX6-10, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.20. Average (± 2 SD) measured and simulated (uniform $C_0 = 76$ ppm) H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-11, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
4.4.4 Initial concentration bracketing study

A bracketing study was performed to demonstrate that the CFD model was representing the physical system correctly. Conceptually, a simulation performed with a uniform pit concentration below the lowest measured initial concentration should produce results that undershoot the measured values at all meter locations in the nursery room. Conversely, using a uniform initial concentration greater than the highest measured value should produce results that overshoot the measured values, effectively bracketing the solution. As the initial concentration becomes progressively greater, the results should match at different meter locations for different initial concentrations.

Twelve simulation cases were run with uniform initial concentrations inside the manure pit varying from 20 to 130 ppm by 10 ppm increments. Table 4.8 lists the initial concentration used for each simulation case and the number of meter locations meeting validation criteria. The results are plotted in Figures 4.21 through 4.35 which show the average measured concentration at each meter location, and simulated curves for initial concentrations of 20 and 130 ppm (the lowest and highest values used in the bracketing study, respectively).
Table 4.8. Initial concentrations used for bracketing study simulation cases and the number of meter locations meeting the validation criteria for each case.

<table>
<thead>
<tr>
<th>Case</th>
<th>Uniform $C_0$</th>
<th>Meeting Criteria</th>
<th>Within 2 SD of Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Slope $#^{b}$</td>
<td>$R^2$ $# &gt; 0.80$</td>
</tr>
<tr>
<td>1</td>
<td>20 ppm$^a$</td>
<td>$1^b$</td>
<td>6$^c$</td>
</tr>
<tr>
<td>2</td>
<td>30 ppm</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>40 ppm</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>50 ppm</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>60 ppm</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>70 ppm</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>80 ppm</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>90 ppm</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>100 ppm</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>110 ppm</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>11</td>
<td>120 ppm</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>12</td>
<td>130 ppm</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

a. Uniform initial $H_2S$ concentration used for the entire manure pit for each simulation case.
b. Number of meter locations meeting the regression slope criteria for each simulation case.
c. Number of meter locations meeting the regression $R^2$ criteria for each simulation case.
d. The average percentage of values within 2 S.D. of the measured curves for all meter locations.
e. Number of meter locations with > 50% of the values within 2 S.D. of the measured curves.
Figure 4.21. Average (± 2 SD) measured and simulated ($C_0 = 20$ and 130 ppm) $\text{H}_2\text{S}$ gas concentration during the first 300s of pit and barn ventilation at meter location TX1-1, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.22. Average (± 2 SD) measured and simulated ($C_0 = 20$ and 130 ppm) $\text{H}_2\text{S}$ gas concentration during the first 300s of pit and barn ventilation at meter location TX1-3, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.23. Average (± 2 SD) measured and simulated ($C_0 = 20$ and $130$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location TX1-2, $0.30$ m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.24. Average (± 2 SD) measured and simulated ($C_0 = 20$ and $130$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location TX1-4, $0.30$ m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.25. Average (± 2 SD) measured and simulated (\(C_0 = 20\) and 130 ppm) \(\text{H}_2\text{S}\) gas concentration during the first 300s of pit and barn ventilation at meter location MX6-1, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.26. Average (± 2 SD) measured and simulated (\(C_0 = 20\) and 130 ppm) \(\text{H}_2\text{S}\) gas concentration during the first 300s of pit and barn ventilation at meter location MX6-2, 0.30 m (12 in.) below the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.27. Average (± 2 SD) measured and simulated ($C_0 = 20$ and $130$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-3, 0.61 m (24 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Figure 4.28. Average (± 2 SD) measured and simulated ($C_0 = 20$ and $130$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-4, 0.61 m (24 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)
Figure 4.29. Average (± 2 SD) measured and simulated ($C_0 = 20$ and $130$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-5, 0.15 m (6 in.) above the floor grating. (Inset plan view image of nursery room shows meter location)

Figure 4.30. Average (± 2 SD) measured and simulated ($C_0 = 20$ and $130$ ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-6, 0.15 m (6 in.) above the floor grating. (Inset plan view image of nursery room shows meter location)
Figure 4.31. Average (± 2 SD) measured and simulated ($C_0 = 20$ and 130 ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-7, 0.15 m (6 in.) above the floor grating. (Inset plan view image of nursery room shows meter location)

Figure 4.32. Average (± 2 SD) measured and simulated ($C_0 = 20$ and 130 ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-8, 0.15 m (6 in.) above the floor grating. (Inset plan view image of nursery room shows meter location)
Figure 4.33. Average (± 2 SD) measured and simulated ($C_0 = 20$ and 130 ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-9, 0.15 m (6 in.) above the floor grating.
(Inset plan view image of nursery room shows meter location)

Figure 4.34. Average (± 2 SD) measured and simulated ($C_0 = 20$ and 130 ppm) $H_2S$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-10, 0.15 m (6 in.) above the floor grating.
(Inset plan view image of nursery room shows meter location)
Figure 4.35. Average (± 2 SD) measured and simulated ($C_0 = 20$ and $130$ ppm) $\text{H}_2\text{S}$ gas concentration during the first 300s of pit and barn ventilation at meter location MX6-11, 0.15 m (6 in.) above the floor grating.

(Inset plan view image of nursery room shows meter location)

Overall, the simulation results bracketed the measured values at many of the meter locations (Table 4.8), even if the shape of the decay curves did not match very well. Due to air movement through the nursery room generally moving from the pit-safety fan location to the barn exhaust fans, the shape of decay curves at meter locations downwind from the pit-safety ventilation fan depends on the initial concentration at upwind locations. In other words, one location that started at a low initial concentration would show a rise in the decay curve if gas from an upwind location at a higher initial concentration arrived. This suggested that a non-uniform initial gas distribution was needed to more closely match the measured data.
4.4.5 Variable $C_0$ based on measured initial spatial values

As noted in Chapter 3, the manure pit initial gas concentration was not uniformly distributed. Thus, a series of simulation cases were run using non-uniform initial conditions inside the manure pit based on observed initial spatial gas concentrations at each meter location inside the pit. The initial concentration was set equal to the measured initial concentration (average of all four replications) at each meter location along the length of the manure pit, and the value was assumed to vary linearly between meter locations by SWFS (Figure 4.36). The divider wall is shown for reference, but the manure level was above the top of the wall during the experiment and the wall did not obstruct air flow.

![Plan view showing linear initial concentration profile used in manure pit with pit-safety fan, agitation manifold, and gas monitor locations (initial concentration listed below each meter).](image)

Table 4.9 and Table 4.10 list the initial concentration values used for each half of the manure pit. The X and Y values listed refer to the origin point shown in Figure 4.36. The initial
pit concentration was assumed to have a constant vertical profile from the top of the manure surface to the bottom of the floor grating. The rest of the nursery room was filled with air (1,000,000 ppm). Values shown in the tables that are not associated with specific meters were based on the assumption that gas was pushed away from the manifold to the far ends of the pit by the agitation end nozzles, and may have drifted to empty areas of the pit by diffusion.

Table 4.9. Linear initial concentration profile in manure pit (from Y = 1.4 to 2.8 m).

<table>
<thead>
<tr>
<th>X (m)</th>
<th>C_initial (ppm)</th>
<th>Meter Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>75</td>
<td>TX1-4</td>
</tr>
<tr>
<td>1.9</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>125</td>
<td>TX1-2</td>
</tr>
<tr>
<td>5.2</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>5.6</td>
<td>71</td>
<td>TX1-3</td>
</tr>
<tr>
<td>7.4</td>
<td>27</td>
<td>TX1-1</td>
</tr>
<tr>
<td>9.2</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>11.1</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10. Linear initial concentration profile in manure pit (from Y = 0.0 to 1.4 m).

<table>
<thead>
<tr>
<th>X (m)</th>
<th>C_initial (ppm)</th>
<th>Meter Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>68</td>
<td>MX6-2</td>
</tr>
<tr>
<td>1.9</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>9.2</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>11.1</td>
<td>46</td>
<td>MX6-1</td>
</tr>
</tbody>
</table>

Most of the gas had been evacuated by 150 seconds, and beyond that time the decay curves for most of the meters were nearly flat. For this reason, only the first 150 seconds of data were considered when comparing simulated results to measured data. Including the data from 150 to 300 seconds would result in improved statistical values for the regression of measured vs.
simulated concentration vs. time. The results of this simulation showed that using a variable initial concentration produced a better match for the measured data at most meter locations, with six meters meeting all of the validation criteria (Table 4.11).

Table 4.11. Statistical criteria for simulated vs. measured gas concentration data for the case with variable initial manure pit concentration based on measured initial spatial values.

<table>
<thead>
<tr>
<th>Height (^a) m (ft)</th>
<th>Meter</th>
<th>Simulated vs. Measured Regression Statistics</th>
<th>Percent within 2 SD (^d)</th>
<th>27% of Average Measured Concentration (^i)</th>
<th># of Criteria Met (^g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.30 m (-12 in.)</td>
<td>TX1-1</td>
<td>Slope (^b) 1.2318, Intercept (^c) 1.1819</td>
<td>56.3</td>
<td>1.2 ppm</td>
<td>All 4</td>
</tr>
<tr>
<td></td>
<td>TX1-3</td>
<td>Slope (^b) 1.1438, Intercept (^c) -2.2791</td>
<td>100.0</td>
<td>3.6 ppm</td>
<td>All 4</td>
</tr>
<tr>
<td></td>
<td>TX1-2</td>
<td>Slope (^b) 1.1549, Intercept (^c) -24.6275</td>
<td>12.5</td>
<td>11.7 ppm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>TX1-4</td>
<td>Slope (^b) 1.2222, Intercept (^c) 0.8367</td>
<td>68.8</td>
<td>8.4 ppm</td>
<td>All 4</td>
</tr>
<tr>
<td></td>
<td>MX6-1</td>
<td>Slope (^b) 1.0817, Intercept (^c) -1.3744</td>
<td>52.3</td>
<td>1.7 ppm</td>
<td>All 4</td>
</tr>
<tr>
<td></td>
<td>MX6-2</td>
<td>Slope (^b) 0.9700, Intercept (^c) 2.4190</td>
<td>78.2</td>
<td>7.7 ppm</td>
<td>All 4</td>
</tr>
<tr>
<td>+0.61 m (+24 in.)</td>
<td>MX6-3</td>
<td>Slope (^b) 3.0866, Intercept (^c) 1.3642</td>
<td>17.2</td>
<td>0.9 ppm</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MX6-4</td>
<td>Slope (^b) 1.4083, Intercept (^c) 3.9975</td>
<td>64.9</td>
<td>3.5 ppm</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>MX6-5</td>
<td>Slope (^b) 0.0475, Intercept (^c) 11.8444</td>
<td>22.5</td>
<td>1.5 ppm</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MX6-6</td>
<td>Slope (^b) -1.0459, Intercept (^c) 4.0272</td>
<td>20.5</td>
<td>0.6 ppm</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>MX6-7</td>
<td>Slope (^b) 1.0126, Intercept (^c) 9.4548</td>
<td>20.5</td>
<td>3.8 ppm</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>MX6-8</td>
<td>Slope (^b) 0.8207, Intercept (^c) 3.5308</td>
<td>60.3</td>
<td>3.8 ppm</td>
<td>All 4</td>
</tr>
<tr>
<td></td>
<td>MX6-9</td>
<td>Slope (^b) 0.9064, Intercept (^c) 10.6924</td>
<td>58.3</td>
<td>2.4 ppm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>MX6-10</td>
<td>Slope (^b) 0.6483, Intercept (^c) -1.8255</td>
<td>36.4</td>
<td>14.4 ppm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>MX6-11</td>
<td>Slope (^b) 0.1134, Intercept (^c) 22.3929</td>
<td>27.8</td>
<td>8.0 ppm</td>
<td>0</td>
</tr>
</tbody>
</table>

a. Vertical height of meter H\(_2\)S sensor with respect to the top of the floor grating.
b. Slope from linear regression of simulated vs. measured H\(_2\)S gas concentration vs. time.
c. Y-intercept from linear regression of simulated vs. measured H\(_2\)S gas concentration vs. time.
d. R\(^2\) value from linear regression of simulated vs. measured H\(_2\)S gas concentration vs. time.
e. Percent of simulated values within ±2 S.D. of the average measured H\(_2\)S gas concentration vs. time.
f. 0.27 × the average measured H\(_2\)S concentration during the first 300s of pit and barn ventilation.
g. The total number of validation criteria met.

Figures 3.37 to 3.49 are graphs of the simulated vs. average (± 2 SD) measured H\(_2\)S gas concentration during the first 300s (5 min) of pit and barn ventilation for the case with variable initial manure pit concentration based on measured initial spatial values at meter locations 0.30 m (12 in.) below, 0.61 m (24 in.) above, and 0.15 m (6 in.) above the floor grating.
Figure 4.37. Average (± 2 SD) measured and simulated H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-1, 0.30 m (12 in.) below the floor grating for the case with variable manure pit C$_0$ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)

Figure 4.38. Average (± 2 SD) measured and simulated H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-3, 0.30 m (12 in.) below the floor grating for the case with variable manure pit C$_0$ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)
Figure 4.39. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-2, 0.30 m (12 in.) below the floor grating for the case with variable manure pit C₀ based on measured initial spatial values. (Inset plan view image of nursery room shows meter location)

Figure 4.40. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-4, 0.30 m (12 in.) below the floor grating for the case with variable manure pit C₀ based on measured initial spatial values. (Inset plan view image of nursery room shows meter location)
Figure 4.41. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-1, 0.30 m (12 in.) below the floor grating for the case with variable manure pit C₀ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)

Figure 4.42. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-2, 0.30 m (12 in.) below the floor grating for the case with variable manure pit C₀ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)
Figure 4.43. Average ($\pm$ 2 SD) measured and simulated H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-3, 0.61 m (24 in.) above the floor grating for the case with variable manure pit C$_0$ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)

Figure 4.44. Average ($\pm$ 2 SD) measured and simulated H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-4, 0.61 m (24 in.) above the floor grating for the case with variable manure pit C$_0$ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)
Figure 4.45. Average (± 2 SD) measured and simulated H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-5, 0.15 m (6 in.) above the floor grating for the case with variable manure pit C$_0$ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)

Figure 4.46. Average (± 2 SD) measured and simulated H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-6, 0.15 m (6 in.) above the floor grating for the case with variable manure pit C$_0$ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)
Figure 4.47. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-7, 0.15 m (6 in.) above the floor grating for the case with variable manure pit Cₒ based on measured initial spatial values. (Inset plan view image of nursery room shows meter location)

Figure 4.48. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-8, 0.15 m (6 in.) above the floor grating for the case with variable manure pit Cₒ based on measured initial spatial values. (Inset plan view image of nursery room shows meter location)
Figure 4.49. Average (± 2 SD) measured and simulated \( \text{H}_2\text{S} \) gas concentration during the first 300s of pit and barn ventilation at meter location MX6-9, 0.15 m (6 in.) above the floor grating for the case with variable manure pit \( C_0 \) based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)

Figure 4.50. Average (± 2 SD) measured and simulated \( \text{H}_2\text{S} \) gas concentration during the first 300s of pit and barn ventilation at meter location MX6-10, 0.15 m (6 in.) above the floor grating for the case with variable manure pit \( C_0 \) based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)
Figure 4.51. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-11, 0.15 m (6 in.) above the floor grating for the case with variable manure pit C₀ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)
4.4.6 Meter response corrections

The simulated gas concentrations from CFD are predicted instantaneous values, but the gas meters used for the experiment do not respond instantaneously to changes in gas concentration. The MX6 and TX1 gas meters use electrochemical sensors to detect H₂S gas (Figure 4.52).

The published specifications for the gas sensors used in the MX6 and TX1 meters (Industrial Scientific Corporation, 2014) state 15s of exposure to a gas concentration is required before the meter reading will equal 50% of that concentration (the T50 value), and 50s is required to attain a reading equal to 90% of the actual concentration (the T90 value). These values were checked in a laboratory using calibration gas with a H₂S concentration of 25 ppm. Figure 4.53
shows a graph of measured H$_2$S concentration vs. time. The sensor appears to behave as a first-order instrument and does not respond immediately to step changes in gas concentration. The sensor must be exposed to a step change in input for some duration of time before the measured gas meter reading will equal the actual concentration level. It was found that the T50 response time was shorter than the published values, reaching 50% of the full reading in 9s. The T90 response time was also shorter, reaching 90% of the full value in 41s.

![Graph of measured H$_2$S concentration vs. time.](image)

**Figure 4.53.** MX6 meter response to a step H$_2$S input of 25 ppm measured in a laboratory.

All but one of the meters located 0.30 m (12 in.) below the floor grating met all statistical criteria. Meter TX1-2 had a -24.63 regression intercept, which was greater than 27% of the average measured concentration at that meter location, 11.65 ppm. Above the floor grating, only one meter met all of the statistical criteria, meter MX6-8, which was located mid-way between
the pit-safety ventilation fan and the barn exhaust fan. The meters located below the floor grating were exposed to H₂S gas for a longer duration of time prior to the start of ventilation: two minutes during manure pit agitation, followed by 30 seconds of barn fan operation to remove any gases that may have escaped from the pit cover during agitation, then 11 seconds to unroll the plastic sheeting before the start of ventilation. Two minutes of exposure was long enough for those meters below the floor to measure the full initial concentration.

Figure 4.54 shows the simulated vs. measured decay curves for meter TX1-2, located 0.30 m (12 in.) below the floor grating. This graph shows typical first-order meter response behavior. The simulated instantaneous gas concentration level (blue line) at that location inside the manure pit fell rapidly. The solid black line, representing the measured gas concentration during manure pit-safety ventilation (average of four replications) decayed rapidly initially, but then slowed and lagged the instantaneous value.

Figure 4.54. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location TX1-2, 0.30 m (12 in.) below the floor grating for the case with variable manure pit C₀ based on measured initial spatial values.  
(Inset plan view image of nursery room shows meter location)
The meters located above the floor started with an initial H$_2$S concentration close to 0 ppm. When the manure pit-safety ventilation fan was turned on, the gas inside the manure pit was exhausted into the barn airspace above through the open floor grating, then evacuated from the room through the barn exhaust fan. The expected gas concentration at a meter located above the floor grating would then start at a H$_2$S concentration of 0 ppm, rise to an initial peak level, then gradually decay back to 0 ppm. The expected first-order sensor response for the gas meter would be delayed in time with a lower peak value.

Figure 4.55 shows meter MX6-11, which was located 0.15 m (6 in.) above the floor closest to the barn exhaust fan. The simulated line (blue) shows predicted instantaneous gas concentrations at that point in space during manure pit-safety ventilation. The solid black line shows the recorded concentration (the average of four replications). The dashed lines represent ±2 standard deviations in the measured values. Compared to the simulated concentration curve, the measured curve displays the type of behavior typical of first-order sensor when exposed to a varying gas concentration. The measured level rises more slowly than the instantaneous value, with an apparent time lag. The measured value never reaches the full peak gas concentration before decaying, which occurs less rapidly than the instantaneous decay curve.
Figure 4.55. Average (± 2 SD) measured and simulated H₂S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-11, 0.15 m (6 in.) above the floor grating for the case with variable manure pit C₀ based on measured initial spatial values. (Inset plan view image of nursery room shows meter location)

Figure 4.56 shows meter MX6-4, which was located 0.61 m (24 in.) above the floor closest to the barn exhaust fan. This graph also shows the type of response expected from a first-order sensor. The simulated instantaneous H₂S concentration starts at 0 ppm, rises sharply after the start of manure pit-safety ventilation to a short plateau between 44 ppm and 47 ppm, then gradually decays back to 0 ppm as H₂S gas is evacuated from the room. The general measured response has a slower response and lags the simulated concentration in time, never reaches the full peak value, then decays more slowly with a time lag back to 0 ppm.
Figure 4.56. Average (± 2 SD) measured and simulated H$_2$S gas concentration during the first 300s of pit and barn ventilation at meter location MX6-4, 0.61 m (24 in.) above the floor grating for the case with variable manure pit $C_0$ based on measured initial spatial values.

(Inset plan view image of nursery room shows meter location)

MX6-11 was in the vicinity of MX6-2 and TX1-4, which were located 0.30 m (12 in.) below the floor. MX6-4 was directly above MX6-2. When compared to the CFD simulation results, these meters exhibit the expected first-order sensor response because they were in the vicinity of portions of the manure pit where the initial conditions were known. i.e. meters MX6-11 and MX6-4 were closest to the barn exhaust fan, and the initial gas concentrations were known at MX6-2 and TX1-4, which were the meters in the pit closest to MX6-11 and MX6-4 above.

Also, gas appeared to move through the manure pit in semi-bulk flow along the line through meters TX1-1 to TX1-4, so gas inside the manure pit that traveled along the line of TX1 meters upwind and the MX6-2 in the nearest corner would have moved past meters MX6-11 and MX6-4 as gas was evacuated from the barn. This means meters MX6-11 and MX6-4 were exposed to the best defined concentrations of H$_2$S gas from the manure pit in terms of initial manure pit conditions, so a match between simulated and measured gas concentrations at these meter
locations is a very good indication that the CFD simulation was accurately representing physical reality.

4.4.6.1 Simple time shifting

Since meters MX6-11 and MX6-4 exhibited time lags typical of first-order sensors, the measured data for meters MX6-11 and MX6-4 were shifted earlier in time to correct for the first-order sensor response. By shifting MX6-11 measured data 29s earlier, all four statistical criteria were met for that location. By shifting MX6-4 measured data 12s earlier, three of the four statistical criteria were met (intercept, $R^2$, and ±2 SD). Figures 4.57 and 4.58 show the simulated and measured concentration curves for meters MX6-11 and MX6-4 after the time shift, respectively. Table 4.12 and Table 4.13 show the statistical criteria for MX6-11 and MX6-4 before and after the time shift, respectively.

![Simulated and measured concentration curves](image)

Figure 4.57. Simulated and average measured C vs. T for MX6-11 after time shift. (Inset plan view image of nursery room shows meter location)
Figure 4.58. Simulated and average measured C vs. T for MX6-4 after time shift.

(Inset plan view image of nursery room shows meter location)

Table 4.12. Statistical criteria for MX6-11 and MX6-4 before time shift.

<table>
<thead>
<tr>
<th>Height m (ft)</th>
<th>Meter</th>
<th>Simulated vs. Measured Regression Statistics</th>
<th>Percent within 2 SD</th>
<th>27% of Average Measured Concentration</th>
<th># of Criteria Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.61 m (+24 in.)</td>
<td>MX6-4</td>
<td>Slope 1.4083, Intercept 3.9975, R² 0.5823</td>
<td>64.90</td>
<td>3.51</td>
<td>1</td>
</tr>
<tr>
<td>+0.15 m (+6 in.)</td>
<td>MX6-11</td>
<td>Slope 0.1134, Intercept 22.3929, R² 0.0119</td>
<td>27.81</td>
<td>8.03</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.13. Improved statistical criteria for MX6-11 and MX6-4 after time shift.

<table>
<thead>
<tr>
<th>Height m (ft)</th>
<th>Meter</th>
<th>Simulated vs. Measured Regression Statistics</th>
<th>Percent within 2 SD</th>
<th>27% of Average Measured Concentration</th>
<th># of Criteria Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.61 m (+24 in.)</td>
<td>MX6-4</td>
<td>Slope 1.8633, Intercept -3.0351, R² 0.8419</td>
<td>83.44</td>
<td>3.67</td>
<td>2</td>
</tr>
<tr>
<td>+0.15 m (+6 in.)</td>
<td>MX6-11</td>
<td>Slope 1.1230, Intercept -8.1519, R² 0.9354</td>
<td>93.38</td>
<td>8.15</td>
<td>All 4</td>
</tr>
</tbody>
</table>
Although the simulated and measured curves aligned better in time, there were still differences in magnitude of peak values. The simulated and average measured concentration curves were normalized to further illustrate the improvement in statistical agreement. Equation 4-3 was used to normalize the curves by subtracting the minimum and dividing by the maximum concentration:

\[
\frac{(C(t) - C_{\text{min}})}{(C_{\text{max}} - C_{\text{min}})}
\]

Figure 4.59 and Figure 4.60 show that the simulated and average measured curves are very similar in shape. The measured curves lag behind the simulated ones both in time required to reach the peak value, and in time required to decay back to zero. This is characteristic of systems that follow a first-order response.

Figure 4.59. Normalized simulated and average measured C vs. T for MX6-11 after time shift. (Inset plan view image of nursery room shows meter location)
Figure 4.60. Normalized simulated and average measured C vs. T for MX6-4 after time shift.

(Inset plan view image of nursery room shows meter location)
4.4.6.2 Transformation of the simulated curve based on first-order response time constant

The time constant, $\tau$, is the duration of time required for a first-order instrument to reach 63.2% of the actual value of the step change in input. Equation 4-4 is the general step response for a first-order instrument with zero initial conditions (Tse & Morse, 1989):

$$y = KA(1 - e^{-t/\tau})$$  \hspace{1cm} 4-4

Where:
- $y$ = measured value
- $K$ = sensitivity
- $A$ = actual step input value
- $t$ = time
- $\tau$ = time constant

The sensitivity is accounted for by the gas meter internally when the electrical measurement across the sensor gets converted to a gas concentration value, therefore a value of $K = 1$ was used. When the instrument is exposed to a change in concentration every second, the step response is dependent on the difference between previous measured and current actual values (Equation 4-5):

$$y(t) = y(t-1) + [A(t) - y(t-1)] \times [1 - e^{1/\tau}]$$  \hspace{1cm} 4-5

Where:
- $y(t)$ = current measured value at time $t$
- $y(t-1)$ = previous measured value
- $A(t)$ = actual step input value at time $t$
- $t$ = time

This can be rewritten in the form of the equation for a line, $y = mx + b$, replacing the slope of the line with $1 - e^{1/\tau}$, $x$ with $[A(t) - y(t-1)]$, and $b$ with $y(t-1)$. From this, time constants of 16.3s, 24.5s, and 49.5s correspond with slope values of 0.06, 0.04, and 0.02, respectively. These slopes were used to calculate the first-order step response for three different time constants.
using Equation 4-5. Figure 4.61 shows that instrument lag time increases for larger time constants.

Figure 4.61. Modeled step response to H₂S input of 25 ppm for a first-order instrument for three different time constants.

Equation 4-5 was applied to transform the simulated gas concentration curves for meters MX6-11 and MX6-4 into the expected first-order instrument response using time constants of 16.3s, 24.5s, and 49.5s. Table 4.14 shows the improved validation criteria statistics. A time constant of 16.3s worked best for MX6-11 with an overall time shift of 14s, with all four statistical criteria being met and higher regression R² and percent of values within ±2 SD than time shifting alone (Figure 4.62). A time constant of 49.5s worked best for MX6-4 with an overall time shift of 40s, with all four statistical criteria being met and improvement in all statistical criteria compared to time shifting alone (Figure 4.63).
Table 4.14. Improved statistical criteria for MX6-11 and MX6-4 after first-order model transformation.

<table>
<thead>
<tr>
<th>Height m (ft)</th>
<th>Meter</th>
<th>Simulated vs. Measured Regression Statistics</th>
<th>Percent within 2 SD</th>
<th>27% of Average Measured Concentration</th>
<th># of Criteria Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.61 m (+24 in.)</td>
<td>MX6-4</td>
<td>Slope 1.1954, Intercept 0.3067, R² 0.8915</td>
<td>98.68</td>
<td>3.47</td>
<td>All 4</td>
</tr>
<tr>
<td>+0.15 m (+6 in.)</td>
<td>MX6-11</td>
<td>Slope 0.9366, Intercept -2.4728, R² 0.9590</td>
<td>100.00</td>
<td>7.90</td>
<td>All 4</td>
</tr>
</tbody>
</table>

Figure 4.62. Simulated and average measured C vs. T for MX6-11 after model transformation. (Inset plan view image of nursery room shows meter location)
Gas meters MX6-4 and MX6-11 were identical models. The operations guides for the MX6 and TX1 meters (Industrial Scientific Corporation, 2014) state that it is normal for the sensors to degrade over time, and regular calibrations are required to adjust for a gradual decline in sensitivity. However, increasing the sensitivity of a first-order instrument often results in a larger time constant and slower response (Tse & Morse, 1989). It is therefore possible that the sensor in MX6-4 was older than the sensor in MX6-11, which would explain the different time constant values.
4.5 Discussion

Overall, the CFD model did a reasonable job of reproducing the observed trends in the nursery room, especially when one considers that the nursery room was a field setting, not a tightly controlled laboratory facility, and that instruments with T90 response times ranging from 14s to 50s were used to measure highly transient gas concentrations. Three of the uncontrolled variables that may have affected the results are listed below:

1. Non-uniform and incomplete definition of initial conditions inside the manure pit.
2. Undefined leakage of gas from beneath the floor during manure pit agitation.
3. Diffusion of gas from beneath the floor during the period of time when the plastic sheeting was removed from the floor after agitation and just prior to ventilation, which would have resulted in non-zero initial H$_2$S concentrations just above the floor grating prior to the start of ventilation.

The results from CFD simulations were highly dependent on the initial gas distribution inside the manure pit. Different assumed or estimated initial gas concentration profiles were investigated to assess how the gas concentration vs. time curves changed at each meter location as a result of changes in initial conditions spatially in the XY plane. The initial vertical concentration profile used in simulations was assumed constant everywhere in the manure pit. It is possible that the actual initial concentration distribution varied with elevation as well as spatially within the manure pit, with some regions above the floor grating with gas concentrations greater than zero just prior to the start of ventilation. In general, using a uniform initial concentration lower than the lowest measured initial concentration resulted in simulated concentration decay curves that were below measured values. Similarly, using a uniform initial concentration greater than the highest measured initial concentration resulted in simulated concentration decay curves that overestimated the measured values.
The simulation results for the meters located inside the manure pit were a better match for the experimental measurements in terms of meeting the validation criteria than the meters located above the floor grating. This may be because these meters were exposed to the initial H₂S gas concentration for a longer duration of time: 2 minutes of agitation, followed by 30 seconds to equilibrate, then 11 seconds to unroll the plastic sheeting before the start of ventilation. The meters located above the floor grating were only exposed to H₂S gas as it was evacuated from the manure pit for a relatively short duration of time. For example, the simulated (with variable C₀) concentration vs. time curve for meter MX6-6 (Figure 4.46) shows a rapid rise to a peak followed by a quick decay in the first 50 seconds. The MX6 meters have advertised Tₕ₀ and T₀₉₀ times of 15s and 50s, respectively. This means that after 15 seconds with a steady input, the meter will only measure 50% of the actual concentration, and it will take 50 seconds at that same steady input level to reach 90% of the full concentration.

Another difference between the model and physical reality is the representation of the floor grating using porous media. The porous media that was used for the simulations was unidirectional, so any flow approaching the porous media at an angle would automatically be turned vertically in the simulations. In reality, there would be some maximum angle a flow vector could follow that would allow relatively unimpeded travel through a slot opening. There would also be some other dynamics happening in that region due to separation and rejoining of flow around solid grating bars, which could further influence the direction of flow as it exits the grating, even possibly acting to turn the flow in the vertical direction.

However, the shape of the simulated concentration decay curves also matches the shape of the measured data at many of the meter locations above the floor grating. For example, MX6-7 shows two peaks separated by a wide plateau and a similar shape (Figure 4.47); MX6-8 shows one peak and a similar shape (Figure 4.48); MX6-10 shows one peak with similar trends (Figure 4.50); and MX6-11 shows similar a shape and trends for the main peak and similar a shape (Figure 4.51). Additionally, the simulated results demonstrated very good agreement with
the experimental measurements after making some reasonable time shifts suggested by meter
time constants and normalization of concentration vs. time curves. This adds further confidence
that the simulation is correctly representing the physical system.

4.6 Model validation conclusions

A series of simulation cases with progressive CFD model improvements and different
initial gas distributions was performed. The best performing gas distribution case, described in
Section 4.4.5, used a variable initial concentration based on average measured initial
concentrations at each meter location inside the manure pit. When comparing simulated to
measured gas concentration curves during manure pit and nursery room ventilation for the best
performing case, 6 out of 15 meters matched without any further processing.

The gas meters used during the nursery room experiment contain sensors that exhibit
first-order response behavior to step changes in gas concentration. Further analysis of meter
locations where validation criteria were not met revealed measurement errors typical of a first-
order system response. This included time lag and differences in magnitude between simulated
and measured curves. By making reasonable shifts to better align the simulated and measured
curves in time, the statistical validation criteria improved for two meters located above the slotted
floor, MX6-4 and MX6-11. Further improvements were attained by applying a first-order
instrument response transformation to the simulated concentration curves for MX6-4 and
MX6-11, bringing the total number of meters that matched simulated data to 8 out of 15. This
strongly suggests that simulations performed using SWFS are adequate for research purposes, and
the CFD simulations have been validated by the measured data.
Chapter 5

Initial Concentration Scaling Method

5.1 Introduction

A trend observed during analysis of CFD simulation results for a given pit and barn shape and ventilation configuration (the same pit-safety fan location and flow rate with the same barn ventilation rate) with different initial manure pit \( \text{H}_2\text{S} \) gas concentrations suggested that the ratio of concentration at each time step during ventilation was equal to the ratio between the initial concentrations inside the manure pit. This relationship was explored using the simulation results from the nursery room initial concentration bracketing study described in Section 4.4.5. It was determined that \( C/C_0 \) scaling could be used to expand the results from one CFD simulation at one \( C_0 \) value to a wide range of \( C_0 \) values.

Normalizing the simulated results and plotting “\( C/C_0 \) vs. Time” gives one graph that can be used to predict the behavior at each meter location for different uniform initial concentration values. Multiplying the concentration decay curve for \( C_0 = 20 \text{ ppm} \) by 2 will yield the decay curve for \( C_0 = 40 \text{ ppm} \). Similarly, \( 3(20) = 60 \), \( 4(20) = 80 \), \( 5(20) = 100 \), \( 6(20) = 120 \). This also works for lower initial concentrations, i.e. multiplying the concentration decay curve for \( C_0 = 20 \text{ ppm} \) by 0.5 will yield the decay curve for \( C_0 = 10 \text{ ppm} \). This illustrates the idea that one initial concentration can be used to determine the decay characteristics for a wide range of different initial concentrations for the same uniform distribution. However, this has not been verified for non-uniform scenarios.

The benefit of using this method was to reduce the total number of simulations needed to estimate the effects of pit-safety ventilation for a range of initial concentrations inside the manure pit. A single simulation was run, and the resulting gas distribution everywhere in the computational domain was deduced for any multiple of the initial concentration used. The
coefficient of variation (c_v), or ratio of standard deviation to the mean, was used to demonstrate the accuracy of this method when compared to actual CFD simulations run for different initial pit concentrations. The purpose of this chapter is to demonstrate the observed trend and show that the C_0 scaling method is valid.

5.2 Background and justification

Gas tracer studies are common in CFD simulations to explore the effects of point source gas release within buildings. First, the steady-state flow field is resolved for the computational domain. This steady-state flow field is then used to define the ambient and boundary conditions for the tracer study. Tracer gas can then be added to the simulation, and transient analysis can be performed to predict how the tracer gas will disperse through the model over time. This approach does not work for manure pit-safety ventilation, however, because gas dispersion occurs from the first moment that the pit-safety ventilation fan is turned on. The first several time steps are critical to accurately predicting the concentration decay of the contaminant gas as the flow field develops.

The initial H_2S gas concentrations used in this research is relatively low compared to the concentration of air, with an initial concentration of 500 ppm making up only 0.05% by volume. At such low relative concentrations, the H_2S gas should not have any significant effect on the carrier fluid or the resulting flow field inside the barn and manure pit air space. The result is that the same flow field develops regardless of initial H_2S concentration. Therefore, once a transient simulation has been performed for one initial H_2S concentration, there should be a way to predict the concentration decay of H_2S gas at other initial concentrations without having to run additional simulations.

This is the case for classical concentration decay equations, where the relationship between concentration at a given time, C(t), is dependent on some flow factors multiplied by the
initial concentration, $C_0$. For example, the simple mixing model in Equation 5-1 that assumes perfect mixing and no source (Albright, 1990) is of the form:

$$C(t) = C_0 e^{(-Q/V)t}$$  \hspace{1cm} 5-1

Where:

- $C(t)$ is the concentration at time $t$ (ppm)
- $Q$ is the volumetric flow rate of ventilation air ($m^3/s$ (cfm))
- $V$ is the volume of the air space being ventilated ($m^3$ (ft$^3$))
- $t$ is time (seconds)

From equation 5-1, for the same ventilation air flow rate and geometry, if the initial concentration, $C_0$, is doubled, the resulting concentration at any time, $C(t)$ will be doubled as well.

### 5.3 Methodology

Simulated gas concentration vs. time results from twelve different CFD simulation cases were analyzed for the Nursery Room (Section 4.4.5). Each simulation case had a different uniform initial manure pit concentration ranging from 20 to 130 ppm. Gas concentration vs. time curves were analyzed for all 15 gas meter locations used in Chapter 4.

At each output time step, $C/C_0$ was calculated for each simulation case at each meter (point) location in the nursery room. $C/C_0$ was also calculated for the global average and maximum concentrations within the computational domain.

The coefficient of variation, $c_v$, was calculated at each output time step (S.D./mean). At the time step when the maximum $c_v$ occurred, the average, minimum, and maximum values of $C/C_0$ were used to determine the confidence limits with respect to the average at each meter.
location. The lower confidence limit was the average value minus the minimum. The upper confidence limit was the maximum minus the average. Since these confidence limits are for the scaled $C/C_0$ from 0 to 1, they represent the maximum percent error in the simulated values.

### 5.4 Results and discussion

Comparisons have been made between the results from twelve CFD simulation cases with different uniform initial manure pit concentrations from the initial concentration bracketing study described in Section 4.4.5. Figure 5.1 shows the simulated $\text{H}_2\text{S}$ concentration during the first 300s of ventilation at meter location MX6-1 for twelve simulations with different uniform initial manure pit $\text{H}_2\text{S}$ concentrations ranging from 20 to 130 ppm in 10 ppm increments.

Figure 5.1. Simulated $\text{H}_2\text{S}$ concentration vs. time for twelve CFD simulations with different $C_0$ values for meter MX6-1 location (first 300s).
A graph of the same data limited to the first 30s of ventilation better illustrates the similarities in the gas decay curves for each initial concentration (Figure 5.2).

Figure 5.2. Simulated H₂S concentration vs. time for twelve CFD simulations with different $C_0$ values for meter MX6-1 location (first 30s only).
Figure 5.3 shows normalizing the simulated concentration value at each time step by dividing $C/C_0$ yields twelve nearly identical curves. Figure 5.4 shows the normalized data during the first 30s of ventilation.

![Graph](image.png)

**Figure 5.3.** $C/C_0$ vs. Time for twelve CFD simulations with different $C_0$ values for meter MX6-1 location (first 300s).
Figure 5.4. $C/C_0$ vs. time for twelve CFD simulations with different $C_0$ values for meter MX6-1 location (first 30s only).

Some divergence in the normalized values occurs as the simulations march forward in time. This can be seen in Figure 5.5, which displays some very small divergence in the normalized values during the last 200s of simulation. Note that the upper $C/C_0$ value of 0.010 (shown on the Y-axis) corresponds to a $H_2S$ concentration of only 1.3 ppm for an initial $H_2S$ concentration of 130 ppm.
Figure 5.5. C/C₀ vs. time for twelve CFD simulations with different C₀ values for meter MX6-1 location (last 200s only).

To quantify the divergence in normalized concentrations, the coefficient of variation (cᵥ) was calculated at each time step for the normalized C/C₀ values of all twelve simulations with different initial concentrations. The coefficient of variation is a measure of dispersion and is defined as the standard deviation divided by the mean (Equation 5-2):

\[ cᵥ = \frac{\sigma}{\mu} \]  

Where:

cᵥ is the coefficient of variation,

σ is the standard deviation,

μ is the mean
At the time step when the maximum \( c_v \) occurred, the average, minimum, and maximum values of \( C/C_0 \) were used to determine the confidence limits with respect to the average at each meter location. The lower confidence limit was the average value minus the minimum. The upper was the maximum minus the average. Since these confidence limits are for the scaled \( C/C_0 \) from 0 to 1, they represent the error range in the simulated values. The same methodology used to analyze the data for meter location MX6-1 was used for the remaining meter locations in the nursery room. Table 5.1 summarizes the resulting statistics for all meter locations.

Table 5.1. Calculated maximum error at each meter location for simulated \( C/C_0 \) for twelve different Nursery Room CFD simulations with \( C_0 \) values from 20 to 130 ppm.

<table>
<thead>
<tr>
<th>Meter Location</th>
<th>Maximum ( c_v ) (%)(^a)</th>
<th>Time (s)(^b)</th>
<th>( C/C_0 ) Value @ Time</th>
<th>Error Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{Avg}^c )</td>
<td>( \text{Min}^d )</td>
<td>( \text{Max}^e )</td>
<td>( \text{Lower}^f )</td>
</tr>
<tr>
<td>MX6-1</td>
<td>8.25</td>
<td>292</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>MX6-2</td>
<td>3.33</td>
<td>186</td>
<td>0.057</td>
<td>0.002</td>
</tr>
<tr>
<td>MX6-3</td>
<td>19.85</td>
<td>300</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td>MX6-4</td>
<td>4.32</td>
<td>264</td>
<td>0.017</td>
<td>0.001</td>
</tr>
<tr>
<td>MX6-5</td>
<td>7.00</td>
<td>297</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>MX6-6</td>
<td>19.78</td>
<td>291</td>
<td>0.008</td>
<td>0.004</td>
</tr>
<tr>
<td>MX6-7</td>
<td>10.39</td>
<td>298</td>
<td>0.016</td>
<td>0.003</td>
</tr>
<tr>
<td>MX6-8</td>
<td>6.88</td>
<td>300</td>
<td>0.018</td>
<td>0.003</td>
</tr>
<tr>
<td>MX6-9</td>
<td>7.27</td>
<td>202</td>
<td>0.098</td>
<td>0.009</td>
</tr>
<tr>
<td>MX6-10</td>
<td>7.44</td>
<td>288</td>
<td>0.021</td>
<td>0.003</td>
</tr>
<tr>
<td>MX6-11</td>
<td>23.54</td>
<td>278</td>
<td>0.030</td>
<td>0.007</td>
</tr>
<tr>
<td>TX1-1</td>
<td>10.70</td>
<td>300</td>
<td>0.006</td>
<td>0.001</td>
</tr>
<tr>
<td>TX1-3</td>
<td>8.26</td>
<td>300</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>TX1-2</td>
<td>8.26</td>
<td>300</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>TX1-4</td>
<td>5.12</td>
<td>300</td>
<td>0.009</td>
<td>0.001</td>
</tr>
<tr>
<td>GG Av(^h)</td>
<td>0.94</td>
<td>299</td>
<td>0.012</td>
<td>0.000</td>
</tr>
<tr>
<td>GG Max(^i)</td>
<td>5.18</td>
<td>262</td>
<td>0.255</td>
<td>0.015</td>
</tr>
</tbody>
</table>

a. Largest \( c_v \) value during the first 300s of simulation at the meter location.
b. Time step when the maximum \( c_v \) occurred.
c. The average \( C/C_0 \) value for all simulations with \( C_0 \) values from 20 to 130 ppm.
d. The minimum \( C/C_0 \) value for all simulations with \( C_0 \) values from 20 to 130 ppm.
e. The maximum \( C/C_0 \) value for all simulations with \( C_0 \) values from 20 to 130 ppm.
f. The lower error limit is equal to the average minus the minimum.
g. The upper error limit is equal to the maximum minus the average.
h. The global average concentration within the computational domain.
i. The global maximum concentration within the computational domain.
The locations with the greatest $c_v$ were MX6-3, MX6-6, and MX6-11. These three meters were located spatially closest to the pit and barn ventilation fans, zones with high velocity gradients. Meter location MX6-3 was 0.6 m (24 in.) above the floor grating, in the corner of the nursery room adjacent to the pit-safety ventilation fan (Figure 5.6). Meter location MX6-6 was 0.15 m (6 in.) above the floor grating, closest to the pit-safety ventilation fan. Meter location MX6-11 was 0.15 m (6 in.) above the floor grating, closest to the small barn exhaust fan (Figure 5.7).

![PLAN VIEW](image)

Figure 5.6. Schematic showing gas measurement locations 0.61 m (24 in.) above the floor.
Figure 5.7. Schematic showing gas measurement locations 0.15 m (6 in.) above the floor.

Meter location MX6-11 had the highest $c_v$ of 23.5% at a time of 278 seconds (Figure 5.8). At 278 seconds, the average, minimum, and maximum $C/C_0$ values for all twelve simulation cases were 0.030, 0.023, and 0.045, respectively. The maximum error from estimations using $C/C_0$ scaling based on these CFD simulations at location MX6-11 is then $0.045 - 0.030 = 0.015$, or 1.5% of the full $C_0$ value in question.
The global average had a maximum $c_r$ of 0.94\% at a time of 299 seconds, but the corresponding error level was the lowest ($\pm 0.000$). The global maximum had a maximum $c_r$ of 5.18\% at a time of 262 seconds, and the corresponding error level was the greatest with a range of $\pm 0.025$, or 2.5\% of the full $C_0$ value in question. An example of using this as the representative error level for the $C_0$ scaling method when compared to these simulations, with an initial $H_2S$ concentration of 1,000 ppm would result in a maximum estimation error of $\pm 25$ ppm. This confidence interval should be applied to the entire computational domain for the full duration of simulations to be conservative.
5.5 Conclusions

The C/C₀ scaling method is a very useful tool because it allows an engineer to estimate contaminated area, maximum concentration, and duration of time required to reach Tₚₑₘ for a wide range of initial pit concentrations for a given barn and manure pit-safety ventilation configuration by running a single CFD simulation. This greatly reduces computational time, allowing the engineer to spend time running different ventilation configuration scenarios rather than running the same scenario multiple times at different initial manure pit concentrations.

The C/C₀ scaling method is a valid method for simulation cases with uniform initial manure pit concentrations. Further study is needed to determine whether this method is applicable when non-uniform initial conditions are specified.

Some divergence occurred in the simulated C/C₀ values for the twelve simulation cases run using different initial manure pit concentrations. This divergence occurred later in the simulation, and it appears that the simulated concentration at each meter location was near or below 20 ppm before the cᵥ began to increase. The ceiling limit for H₂S exposure by humans during an 8-hour work day is 20 ppm. The cᵥ represents the error between the simulated values at each time step. If the H₂S concentration has decayed below the acceptable ceiling limit, error in the simulated values is of less concern as the simulations march forward in time.

However, the calculated cᵥ values were for different simulations. By performing one simulation and multiplying the results at each time step by the desired ratio of new C₀ value to original simulated C₀ value, predicted results for the same pit and barn configuration can be estimated for the new C₀ value. The cᵥ for this new data set should equal zero because it is derived from the original simulation. The cᵥ may then be more useful as a measure of convergence when selecting grid and time step sizes for CFD simulations. Further study is needed to determine the source of error between simulated values at different initial concentrations when compared to estimated values using the C/C₀ scaling method.
Application of this method depends on the initial concentration range being studied and the acceptable level of error. The error when using the C/C₀ scaling method was lowest for the global average concentration (± 0.0%). The maximum error when comparing simulated to estimated C/C₀ values was ± 2.5% for the global maximum concentration over time. For practical purposes for Phase II and III of this study, a safe C₀ limit of 500 ppm was selected for estimation purposes. With an error level of ± 2.5%, the estimation uncertainty would be ± 12.5 ppm when the simulated initial H₂S concentration is 500 ppm.
Chapter 6

Phase II Tunnel Ventilated Barn Simulations

6.1 Introduction

This chapter describes simulations that were performed for a 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long) tunnel ventilated (TV) barn located above a full-sized manure pit with a fully-slotted cover. Manure pit-safety ventilation fan configuration (location and flow rate) was varied to simulate the resulting distribution of \( \text{H}_2\text{S} \) gas in the barn airspace during a barn and manure pit-safety ventilation event. Simulation results for each pit-safety fan configuration were analyzed to determine the affected area in the barn and the duration of time when the concentration of \( \text{H}_2\text{S} \) gas was 50 ppm or greater, the maximum \( \text{H}_2\text{S} \) concentration in the barn airspace, and ventilation time required to reach \( T_{pel} \) in the manure pit. The purpose of research efforts reported in this chapter was to identify zones within tunnel ventilated barns with fully-slotted floors located above full-sized mechanically-ventilated manure pits that must be evacuated for ratios of manure pit to barn ventilation air flow rates (\( Q_{pit}/Q_{barn} \)) that result in pit gases being exhausted into the barn airspace.

6.2 Methodology

CFD simulations were performed for a tunnel ventilated barn located above a full-sized manure pit with a fully-slotted cover. The fully-slotted floor was represented using porous media as described in section 6.2.6.7. Grid and time step sensitivity studies were performed to select appropriate grid and time step sizes for the transient simulations. CFD simulations were then performed with different pit-safety ventilation fan locations and flow rates.
The simulations were run until the maximum concentration of H$_2$S gas inside the manure pit was < 1.0 ppm with an initial concentration of 100 ppm. Results for other initial gas concentrations (200, 300, 400, and 500 ppm) were deduced from the 100 ppm simulations using the C$_0$ scaling method described in Chapter 5. Selected simulations were continued until the maximum pit concentration was < 0.2 ppm so the results could be multiplied by a factor of 5 (to represent an initial pit concentration of 500 ppm) to determine the duration of time required to reach a final concentration of 1 ppm inside the pit. However, most of the data analysis focused on the first 300 s (5 min) of pit-safety ventilation.

The simulation results were processed to determine the percent of the total barn area on a reference plane located 0.15 m (6 in.) above the barn floor with a H$_2$S concentration ≥ 50 ppm. The maximum barn H$_2$S concentration and the total time the maximum value was ≥ 50 ppm during the first 300s of ventilation were also determined.

6.2.1 Pit and barn details and dimensions

A 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long) barn with a ceiling height of 3.05 m (10 ft) was selected as the physical system for this study. This size is representative of some common configurations for animal housing, and can be effectively ventilated using tunnel or cross-ventilation schemes. The manure pit underneath the barn had the same length and width dimensions as the barn with a depth of 2.44 m (8 ft). Only fully slotted floors were considered. The barn ventilation air flow rate, Q$_{\text{barn}}$, was based on the hot weather maximum ventilation rate for the selected building size and design animal stocking density (ASABE, 2017a; Midwest Plan Service, 1983). The pit-safety ventilation air flow rate, Q$_{\text{pit}}$, was calculated from Q$_{\text{barn}}$ and the ratio of Q$_{\text{pit}}$/Q$_{\text{barn}}$ used for each pit and barn configuration. Design calculations for ventilation requirements based on hot weather maximum ventilation rates for the selected barn size and number of animals are described in section 6.2.6.5.
Details and critical dimensions for the selected pit and barn configurations are listed below:

1. Barn inside dimensions: 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long)
2. Height to barn ceiling: 3.05 m (10 ft)
3. Full-sized pit dimensions: same width and length as barn above, 2.44 m (8 ft) depth.
4. Pit cover and slot dimensions: 0.15 m (6 in.) thick cover, fully-slotted with 50.8 mm (2.0 in.) slot width and 0.15 m (6 in.) slat width, with slots orientated perpendicular to the length of the barn.
5. Pit/barn limitations: It was assumed that 0.15 m (6 in.) or less of manure remained in the storage prior to ventilation and entry (no source of H2S gas emission); no foaming, agitation, dividers, support columns, or other obstructions were present in the pit.
6. Tunnel ventilated barn ventilation:
   a. Fan outlet end wall layout: One continuous opening 11.59 m wide × 2.44 m high (38 ft wide × 8 ft high) inside a 0.30 m (1 ft) solid perimeter, with uniform outlet velocity assumed over the entire surface of the opening.
   b. Inlet end wall layout: One continuous opening 11.59 m wide × 2.74 m high (38 ft wide × 9 ft high) with a 0.30 m (1 ft) solid perimeter along the barn walls and ceiling, with uniform inlet air velocity assumed over the entire surface of the opening.
7. The barn floor was 0.15 m (6 in.) thick, and was placed between the pit and barn so that the overall distance from the pit floor to the barn ceiling was 5.64 m (18.5 ft).
8. The influence of animals on airflow in the barn was ignored for this first study of barn contamination during positive pressure safety ventilation of manure pits.
Figure 6.1 shows the pit-safety ventilation fan locations that were used for barns with fully slotted floors located above full-sized manure pits. Simulations performed using these fan locations cover most real-world scenarios that might be encountered when ventilating a manure pit located beneath barns without pump-out ports around the building perimeter. Additionally, the results from simulations with fans at these locations should provide insight about the behavior of fans placed at intermediate locations.

In the TV barn simulation cases, the X-axis is defined as the longitudinal centerline, which is also the line of symmetry in the barn. Due to symmetry conditions that exist in the barn, it was not necessary to simulate the locations indicated in Figure 6.1 by dashed red circles in the negative Y-direction. Table 6.1 lists the X and Y coordinates for the five pit-safety ventilation fan locations used.
Figure 6.1. Fan locations used for the tunnel ventilated barn with a full-sized manure pit.

Table 6.1. Fan locations for tunnel ventilated simulation cases.

<table>
<thead>
<tr>
<th>Fan Location</th>
<th>Fan X m (ft)</th>
<th>Fan Y m (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,1</td>
<td>29.3 m (96.0 ft)</td>
<td>4.88 m (16.0 ft)</td>
</tr>
<tr>
<td>1,2</td>
<td>29.3 m (96.0 ft)</td>
<td>0.00 m (0.0 ft)</td>
</tr>
<tr>
<td>2,2</td>
<td>15.24 m (50.0 ft)</td>
<td>0.00 m (0.0 ft)</td>
</tr>
<tr>
<td>3,1</td>
<td>1.22 m (4.0 ft)</td>
<td>4.88 m (16.0 ft)</td>
</tr>
<tr>
<td>3,2</td>
<td>1.22 m (4.0 ft)</td>
<td>0.00 m (0.0 ft)</td>
</tr>
</tbody>
</table>

*Fan X and Y coordinates are with respect to the origin shown on Figure 6.1.
(0,0) is along the longitudinal centerline at the inlet end of the barn.
6.2.2 Parallel flow and counterflow terminology

The terms “parallel flow” and “counterflow” are used in this document to characterize the relative directions of barn and pit-safety ventilation air flow TV simulation cases. Parallel flow refers to the case when the direction of bulk air flow is the same for the manure pit and barn (Figure 6.2a). Counterflow refers to the case when the direction of bulk air flow in the pit is opposite that of the barn (Figure 6.2b). By these definitions, fan locations (1,1) and (1,2) are considered counterflow, and fan locations (3,1) and (3,2) are considered parallel flow.

Figure 6.2. (a) Parallel flow and (b) counterflow definition for a tunnel ventilated barn above a full-sized manure pit.
6.2.3 Simulation case naming convention

A naming convention was used for all simulation cases performed for the tunnel ventilated barns. The simulation case TV32Qr30 denotes the simulation was for a fully-slotted pit cover, a full-sized pit, with a tunnel ventilated barn located above, with the pit-safety fan at location (3,2), and Qr30 represents a pit-safety fan flow rate 1/30 that of the barn exhaust fans. A breakdown is shown below, followed by abbreviation definitions:

TV 32 Qr30

Where:

TV = Tunnel ventilated barn

32 = Pit-safety fan Location (3,2) – Figure 6.1

Qr30 = Fan case for $Q_p/Q_b$ ratio 1/30

Simulation cases were also conducted with no pit-safety ventilation fan as a baseline for fan location and flow rate comparisons. For the cases where no pit-safety ventilation fan was used, “No Fan” appears instead of an abbreviation.
6.2.4 Schedule of simulations

A list of the simulations run for Phase II of this study is presented in Table 6.2. The table lists the fan cases \(Q_r\), the corresponding \(Q_p/Q_b\) ratio, and the actual pit-safety ventilation fan flow rate \(Q_p\) simulated at each pit-safety fan location in the barn.

Table 6.2. Schedule of simulations run for Phase II tunnel ventilated barn model.

<table>
<thead>
<tr>
<th>Case</th>
<th>(Q_r)</th>
<th>(Q_p/Q_b)</th>
<th>(Q_p) (m^3/s) (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV11</td>
<td>120</td>
<td>1/120</td>
<td>0.9 (m^3/s) (2,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>1.9 (m^3/s) (4,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>3.8 (m^3/s) (8,000 cfm)</td>
</tr>
<tr>
<td>TV12</td>
<td>120</td>
<td>1/120</td>
<td>0.9 (m^3/s) (2,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>1.9 (m^3/s) (4,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>3.8 (m^3/s) (8,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1/15</td>
<td>7.6 (m^3/s) (16,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1/8</td>
<td>15.1 (m^3/s) (32,000 cfm)</td>
</tr>
<tr>
<td>TV22</td>
<td>120</td>
<td>1/120</td>
<td>0.9 (m^3/s) (2,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>1.9 (m^3/s) (4,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>3.8 (m^3/s) (8,000 cfm)</td>
</tr>
<tr>
<td>TV31</td>
<td>120</td>
<td>1/120</td>
<td>0.9 (m^3/s) (2,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>1.9 (m^3/s) (4,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>3.8 (m^3/s) (8,000 cfm)</td>
</tr>
<tr>
<td>TV32</td>
<td>120</td>
<td>1/120</td>
<td>0.9 (m^3/s) (2,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>1.9 (m^3/s) (4,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>3.8 (m^3/s) (8,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1/15</td>
<td>7.6 (m^3/s) (16,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1/8</td>
<td>15.1 (m^3/s) (32,000 cfm)</td>
</tr>
<tr>
<td>No Fan</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: \(Q_b\) for all TV cases was 113.3 \(m^3/s\) (240,000 cfm).
6.2.5 Phase II CFD model

The tunnel ventilated barn was represented by a thin 3D shell with open ends (normal to the direction of barn airflow) and completely closed sidewalls. One end represented the outlet for the barn ventilation fans, and the opposite end represented the fresh air inlet (Figure 6.3).

![Figure 6.3. CFD model for the tunnel ventilated barn.](image)

6.2.6 CFD model settings

This section describes the general settings used in SWFS for the CFD models tunnel ventilated barns. These settings were also used for the cross-ventilated barns reported in Chapter 7. Gravity was set to -9.8 m/s² (-32.2 ft/s²). Standard temperature and pressure were specified for ambient conditions (20.0°C (68°F) and 101.3 kPa (14.7 psi), respectively). A summary printout of these CFD model settings from SWFS is presented in Appendix C.
6.2.6.1 Turbulence model parameters

The initial conditions prior to turning on the pit and barn fans were quiescent (still air). Since values of zero were not allowed by the software, the initial parameters for turbulence intensity ($I$) and length ($l$) used in the k-ε turbulence model were set nearly equal to zero ($I = 1 \times 10^{-6} \%$ and $l = 2.54 \times 10^{-8}$ m ($1 \times 10^{-6}$ in.), respectively). These values were used for initial conditions for the room airspace and environmental pressure openings. For the pit-safety ventilation fan, the initial turbulence values were set equal to $I = 5\%$ and $l = 123.44$ mm (4.86 in., the value set by SWFS as a default for the selected geometry).

6.2.6.2 Gas concentrations

The only fluids in the computational domain were air (using the default fluid definition in SWFS) and hydrogen sulfide gas. Initial concentrations were specified using the volume fraction (ppm) of each gas. Initially, only atmospheric air with a concentration of 1,000,000 ppm was specified everywhere in the barn airspace above the slotted floor. This value was also used for air entering from environmental pressure openings and the ducted pit-safety ventilation fan. Simulations were performed for all cases using a uniform 100 ppm initial $H_2S$ concentration inside the manure pit, with the remainder of the total concentration by volume consisting of air.

6.2.6.3 Goals and convergence criteria

All simulations were run until the maximum volume fraction of $H_2S$ gas inside the manure pit decayed to less than 1.0 ppm with an initial concentration of 100 ppm. A few cases were extended until the maximum volume fraction of $H_2S$ gas inside the manure pit decayed to less than 0.2 ppm to ensure that multiplying the results by a factor of 5 (to represent an initial pit
concentration of 500 ppm) would have a value for $T_{pel}$ at a final concentration of 1 ppm inside the pit.

Because the simulation was transient, all other convergence criteria, called goals in SWFS, were only used to track the values of solution variables during the calculations. Global average values for pressure, turbulent energy, turbulent dissipation, velocity (magnitude, in the X, Y, and Z directions), and mass of fluid were saved at each 0.25 second interval of the simulation. The global average and maximum volume fraction of hydrogen sulfide gas were also saved.

For the barn airspace, a plane located 0.15 m (6 in.) above the barn floor was selected as the threshold height to determine if toxic levels of $H_2S$ gas were being evacuated into the barn airspace above the manure storage during ventilation. The 0.15 m (6 in.) height was selected to consider the breathing space of piglets, which are the smallest animals typically confined inside a barn located above a confined-space manure storage. Point parameters were used to track $H_2S$ concentrations at 1,000 point locations on the measurement plane located 0.15 m (6 in.) above the barn floor plane (Figure 6.4).
Figure 6.4. TV barn model with 1,000 grid points placed on the 0.15 m (6 in.) barn measurement plane.

6.2.6.4 Boundary conditions

Boundary conditions and model parameters were based on measured values wherever possible. To simplify the geometry and mesh of the CFD model, it was assumed that the interior walls and ceiling of the barn were sheathed with no exposed framing members. The interior of the barn was modeled with adiabatic smooth surfaces with a roughness height of 0 µm (0 µin.).
6.2.6.5 Tunnel ventilated barn exhaust fans

In a typical tunnel ventilated barn, multiple exhaust fans are located at the outlet end of the barn, and the barn doors and other flow openings in the outlet end wall are closed to prevent short circuiting of air flow. At the opposite end of the barn, where the inlet air enters from the outside environment, all doors and other flow openings are fully opened to allow fresh air to be drawn into the barn. A 0.3 m (1.0 ft) solid border was placed inside the walls and ceiling at that end of the barn to represent the typical flow transition from air being drawn through the end wall openings to a uniform bulk velocity through the barn (Figure 6.5).

To simplify the tunnel ventilated CFD model, the barn exhaust fans were represented by a uniform outlet velocity boundary condition applied to a lid that covered the entire outlet face of the barn. A 0.3 m (1.0 ft) solid border was placed around the perimeter of that end of the barn to represent the typical flow transition from a uniform bulk velocity through the barn to the exhaust fan inlets (Figure 6.6). The design air velocity inside the barn was 3.1 m/s (600 ft/min, or 10 ft/s). The total air flow rate, $Q_{\text{barn}}$, required to maintain that velocity was 113.3 m$^3$/s (240,000 cfm). The velocity at the outlet boundary condition was calculated from the area of the end wall opening and the total air flow rate:

$$V = \frac{Q}{A} = \frac{113.3 \ m^3/s}{28.2 \ m^2} = 4.0 \ m/s$$

$$V = \frac{Q}{A} = \frac{240,000 \ cfm}{304 \ ft^2} = 13.2 \ ft/s$$

The TV barn exhaust fans were represented by an Outlet Velocity boundary condition applied to the interior surface of a lid that was placed over the barn end wall opening in the model (Figure 6.7).
Figure 6.5. Tunnel ventilated barn inlet end wall details.

Figure 6.6. Tunnel ventilated barn exhaust end wall details.
Figure 6.7. Schematic of the TV barn model and boundary conditions.
**6.2.6.6 Pit-safety ventilation fan**

Ducted fresh air was assumed for the pit-safety ventilation fan inlet, but no solid geometry was included in the CFD model to represent the inlet air ducting. A solid cylinder with a thickness of 76 mm (3 in.) was used to represent the pit-safety ventilation fan. The cylinder was placed within a hole through the barn floor, and the outlet face of the pit-safety fan was located 76 mm (3 in.) below the top of the floor. A 6.4 mm (1/4 in.) thick solid border was placed at the outside of the fan cylinder diameter to represent the fan housing and to create a gap between the slotted floor and the pit-safety ventilation fan boundary condition (Figure 6.8).

![Cross-sectional view of pit-safety ventilation fan location in slotted barn floor.](image)

A local initial mesh refinement level of two was applied to the fan inlet surface to divide the mesh at that location into smaller rectangles to more accurately capture the integrated surface area of the circular inlet (m² (ft²)) which determined the air flow rate used in calculations (Q = V×A). This was necessary because the modeled pit-safety fan inlet surface was represented by simplified geometry defined by a circle drawn on a flat plate. A single pit-safety fan velocity of 13.0 m/s (42.4 ft/s) was selected for all simulation cases. This was based on a review of commercially available axial safety ventilation fans. These fans have smaller diameters than
other commercially available portable ventilation fans because they are sometimes used with ducting that needs to be small enough to fit in a manhole or opening and still allow a person to fit through the opening. The outside diameter of the fan geometry used in the CFD model was then adjusted for each simulation case based on the required flow rate for each ratio of $Q_p/Q_b$. The resulting pit-safety fan diameters used for the tunnel ventilated simulation cases are listed in Table 6.3. Two additional $Q_p/Q_b$ ratios were used to explore the effects of much larger pit-safety ventilation fan flow rates for two selected fan locations for the tunnel ventilated barn (Table 6.4).

Table 6.3. Pit-safety ventilation fan diameters used for tunnel ventilated barn cases.

<table>
<thead>
<tr>
<th>Fan Case</th>
<th>$Q_{barn}$ m$^3$/s (cfm)</th>
<th>$Q_p/Q_b$ ratio</th>
<th>$V$ m/s (ft/s)</th>
<th>$Q_{pit}$ m$^3$/s (cfm)</th>
<th>$A$ m$^2$ (ft$^2$)</th>
<th>Dia. m (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qr30</td>
<td>113.3 (240,000)</td>
<td>1/30</td>
<td>13.0 (42.4)</td>
<td>3.8 (8,000)</td>
<td>0.3 (3.1)</td>
<td>0.6 (24.0)</td>
</tr>
<tr>
<td>Qr60</td>
<td>113.3 (240,000)</td>
<td>1/60</td>
<td>13.0 (42.4)</td>
<td>1.9 (4,000)</td>
<td>0.2 (1.6)</td>
<td>0.4 (17.0)</td>
</tr>
<tr>
<td>Qr120</td>
<td>113.3 (240,000)</td>
<td>1/120</td>
<td>13.0 (42.4)</td>
<td>0.9 (2,000)</td>
<td>0.1 (0.8)</td>
<td>0.3 (12.0)</td>
</tr>
</tbody>
</table>

Table 6.4. Additional pit-safety ventilation fan diameters used for selected TV barn cases.

<table>
<thead>
<tr>
<th>Fan Case</th>
<th>$Q_{barn}$ m$^3$/s (cfm)</th>
<th>$Q_p/Q_b$ ratio</th>
<th>$V$ m/s (ft/s)</th>
<th>$Q_{pit}$ m$^3$/s (cfm)</th>
<th>$A$ m$^2$ (ft$^2$)</th>
<th>Dia. m (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qr8</td>
<td>113.3 (240,000)</td>
<td>1/8</td>
<td>13.0 (42.4)</td>
<td>15.1 (32,000)</td>
<td>1.2 (12.6)</td>
<td>1.2 (48.0)</td>
</tr>
<tr>
<td>Qr15</td>
<td>113.3 (240,000)</td>
<td>1/15</td>
<td>13.0 (42.4)</td>
<td>7.6 (16,000)</td>
<td>0.6 (6.3)</td>
<td>0.9 (34.0)</td>
</tr>
</tbody>
</table>
6.2.6.7 Porous media used to represent slotted flooring

The modeled barn floor had overall dimensions of 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long). Precast concrete slotted floor sections 1.22 m wide × 3.05 m long × 0.15 m thick (4 ft wide × 10 ft long × 6 in. thick) were selected for the barn floor. Typical 3.05 m (10 ft) long slotted flooring sections have a crossing rib at mid-length, and the outer longitudinal edges are formed to contain half of a slot (Figure 6.9a). The resulting section contains six full slats and five slot openings.

To simplify the geometry for use in a simulated wind tunnel, the crossing rib was omitted and the slotted floor section was modeled with five full slats and six slot openings (with half slats along the outer longitudinal edges). The modeled slotted flooring section was 1.22 m wide × 3.05 m long (4 ft wide × 10 ft long) with 0.15 m (6 in.) wide slats and 50.8 mm (2 in.) wide slots that extended to within 76.2 mm (3 in.) of each end of the section. The resulting section had 23.8% open area (Figure 6.9b).
Figure 6.9. Standard (a) and modeled (b) slotted floor sections.

It was assumed that the slotted flooring acts as a uniform resistance to air flow. To avoid an unnecessarily dense mesh in the region of the slotted flooring, a porous medium was defined with the same flow characteristics as the slotted flooring. The slotted flooring was simulated in a modeled wind tunnel (Figure 6.10) with ideal (frictionless) walls, so that the only resistance to flow was due to the flooring itself. Note that the slotted flooring and the pit-safety ventilation fan air flow rates used for Phase II simulations differ from those described in Section 4.3.6, and a separate wind tunnel study was needed to properly characterize the flow resistance characteristics of the precast concrete slotted flooring.
The slotted flooring section was placed at the center of the wind tunnel length. The tunnel extended for a length of 3.05 m (10 ft) on both sides of the grating. One end of the tunnel had an inlet volume flow rate boundary condition, and the other end was defined as an opening at environmental pressure.

A steady-state parametric study was performed to determine the pressure drop across the slotted flooring over a range of air flow rates from 0.02 to 4.72 m³/s (50 to 10,000 cfm) (Table 6.5). The pressure drop was defined as the difference in pressure measured at the top and bottom surfaces of the flooring.
Table 6.5. Slotted flooring and porous media simulation results (pressure drop vs. flow rate).

<table>
<thead>
<tr>
<th>Q (m$^3$/s)</th>
<th>Slotted Flooring Pressure Drop (Pa)</th>
<th>Porous Media Pressure Drop (Pa)</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>1.43</td>
</tr>
<tr>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
<td>1.35</td>
</tr>
<tr>
<td>0.12</td>
<td>0.02</td>
<td>0.02</td>
<td>1.61</td>
</tr>
<tr>
<td>0.24</td>
<td>0.08</td>
<td>0.08</td>
<td>0.73</td>
</tr>
<tr>
<td>0.47</td>
<td>0.32</td>
<td>0.33</td>
<td>0.74</td>
</tr>
<tr>
<td>0.94</td>
<td>1.26</td>
<td>1.27</td>
<td>0.62</td>
</tr>
<tr>
<td>1.42</td>
<td>2.44</td>
<td>2.46</td>
<td>0.80</td>
</tr>
<tr>
<td>1.89</td>
<td>4.97</td>
<td>5.00</td>
<td>0.59</td>
</tr>
<tr>
<td>2.36</td>
<td>7.74</td>
<td>7.79</td>
<td>0.66</td>
</tr>
<tr>
<td>3.54</td>
<td>17.39</td>
<td>17.52</td>
<td>0.73</td>
</tr>
<tr>
<td>4.72</td>
<td>34.00</td>
<td>34.20</td>
<td>0.58</td>
</tr>
</tbody>
</table>

A unidirectional porous medium was then created using the pressure drop vs. flow rate values from simulations using the slotted flooring geometry, and the flooring in the simulation was replaced with the porous medium. The simulation cases were then repeated to verify that the porous medium created an equivalent resistance to flow. The resulting pressure drop across the porous medium was within 1.61% of the values obtained using the slotted flooring geometry (Table 6.5).
6.2.6.8 Grid convergence study

A grid convergence study was performed to quantify the level of uncertainty in the simulation coming from the discretized computational grid. The candidate meshes divided the computational domain into a number of cells of equal length in the X, Y, and Z directions, denoted \( N_x \), \( N_y \), and \( N_z \), respectively. A mesh refinement factor of 1.1 was used to increase the number of cells in each direction for successive cases. A local mesh refinement level of 2 was used at the pit-safety ventilation fan outlet surface to more accurately capture the full surface area. Table 6.6 shows the candidate mesh levels used for the grid convergence study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cells ((N_x,N_y,N_z))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100,40,18</td>
</tr>
<tr>
<td>2</td>
<td>110,44,20</td>
</tr>
<tr>
<td>3</td>
<td>120,48,22</td>
</tr>
<tr>
<td>4</td>
<td>132,52,24</td>
</tr>
<tr>
<td>5</td>
<td>144,58,26</td>
</tr>
<tr>
<td>6</td>
<td>158,64,28</td>
</tr>
<tr>
<td>7</td>
<td>172,70,31</td>
</tr>
<tr>
<td>8</td>
<td>190,78,34</td>
</tr>
<tr>
<td>9</td>
<td>206,84,37</td>
</tr>
<tr>
<td>10</td>
<td>248,100,44</td>
</tr>
</tbody>
</table>

Simulations were performed using the largest \( Q_{pit} \) and \( Q_{barn} \) values included in this study. As the worst case, the grid size determined using the highest fan velocities should produce acceptable results when lower \( Q_{pit} \) and \( Q_{barn} \) values are used with the same grid size. In other words, the same mesh size should be satisfactory to use for the full range of \( Q_{pit} \) and \( Q_{barn} \) values used for this study.
The simulations did not converge monotonically. Since the variable of interest was the integral concentration of H$_2$S gas in the computational domain during the first 300 seconds (5 min.) of ventilation, the global average (Global C$_{avg}$) volume fraction of H$_2$S gas was used to establish grid convergence. Transient simulations were performed using a 1.0 second time step size. The area under the C$_{avg}$ vs. time curve was integrated, and the integral values were compared to determine the percent difference between subsequent mesh levels. The integrated maximum (Planar C$_{max}$) and average (Planar C$_{avg}$) concentrations on the plane located 0.15 m (6 in.) above the slotted floor were used to further assess grid convergence.

The integral differences between Case 5 and Case 6 (Table 6.7) were 0.17%, 4.88%, and 3.59%, respectively, for global average concentration, and maximum and average concentrations at the measurement plane located 0.15 m (6 in.) above the slotted floor. Therefore, Case 5 was selected for use in the Phase II simulations. A summary of the final grid dimensions can be found in Table 6.8. Figure 6.11 is a cross section of the barn and manure pit showing the selected mesh.

Table 6.7 Difference (%) between subsequent mesh levels for Phase II grid convergence study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cells $(N_x,N_y,N_z)$</th>
<th>Integrated Global C$_{avg}$</th>
<th>Difference</th>
<th>Integrated Planar C$_{max}$</th>
<th>Difference</th>
<th>Integrated Planar C$_{avg}$</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100,40,18</td>
<td>998.1</td>
<td>-</td>
<td>6,463.7</td>
<td>-</td>
<td>673.3</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>110,44,20</td>
<td>871.1</td>
<td>13.60</td>
<td>6,225.0</td>
<td>3.76</td>
<td>554.5</td>
<td>19.35</td>
</tr>
<tr>
<td>3</td>
<td>120,48,22</td>
<td>879.7</td>
<td>0.99</td>
<td>6,349.7</td>
<td>1.98</td>
<td>555.3</td>
<td>0.14</td>
</tr>
<tr>
<td>4</td>
<td>132,52,24</td>
<td>884.1</td>
<td>0.50</td>
<td>6,591.5</td>
<td>3.74</td>
<td>564.4</td>
<td>1.64</td>
</tr>
<tr>
<td>5</td>
<td>144,58,26</td>
<td>895.7</td>
<td>1.30</td>
<td>5,842.0</td>
<td>12.06</td>
<td>396.8</td>
<td>34.89</td>
</tr>
<tr>
<td>6</td>
<td>158,64,28</td>
<td>897.2</td>
<td>0.17</td>
<td>6,134.0</td>
<td>4.88</td>
<td>411.3</td>
<td>3.59</td>
</tr>
<tr>
<td>7</td>
<td>172,70,31</td>
<td>918.6</td>
<td>2.35</td>
<td>6,543.6</td>
<td>6.46</td>
<td>443.6</td>
<td>7.56</td>
</tr>
<tr>
<td>8</td>
<td>190,78,34</td>
<td>918.2</td>
<td>0.04</td>
<td>6,836.4</td>
<td>4.38</td>
<td>451.1</td>
<td>1.67</td>
</tr>
<tr>
<td>9</td>
<td>206,84,37</td>
<td>922.8</td>
<td>0.51</td>
<td>6,961.7</td>
<td>1.82</td>
<td>460.7</td>
<td>2.12</td>
</tr>
<tr>
<td>10</td>
<td>248,100,44</td>
<td>915.9</td>
<td>0.76</td>
<td>7,661.8</td>
<td>9.58</td>
<td>485.4</td>
<td>5.22</td>
</tr>
</tbody>
</table>

Note: Difference (%) is a comparison between the current and previous value, where Difference (%) = \(|\text{Previous} - \text{Current}| / [(\text{Previous} + \text{Current}) / 2] * 100\)
Table 6.8. Final mesh dimensions used for Phase II simulations.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nx</td>
<td>144</td>
</tr>
<tr>
<td>Ny</td>
<td>58</td>
</tr>
<tr>
<td>Nz</td>
<td>26</td>
</tr>
<tr>
<td>Total Cells</td>
<td>220,658</td>
</tr>
<tr>
<td>Fluid Cells</td>
<td>193,054</td>
</tr>
<tr>
<td>Solid Cells</td>
<td>780</td>
</tr>
<tr>
<td>Partial Cells</td>
<td>26,824</td>
</tr>
</tbody>
</table>
Figure 6.11. Final mesh with $144 \times 58 \times 26$ cells ($N_x \times N_y \times N_z$) for Phase II simulations.
6.2.6.9 Time step convergence study

A time step convergence study was performed to quantify the level of uncertainty coming from the size of the discretized time steps used to perform transient simulations. The selected mesh Case 5 was utilized, and transient simulations were performed using gradually smaller time step sizes (decreasing by a factor of two) until the value of the variable of interest changed by less than 10% between subsequent refinements. The tradeoff between error level and time step size is computational time, which increases as the time step gets further reduced. Table 6.9 shows the candidate time step sizes used for the time step convergence study.

Table 6.9. Candidate time step sizes used for the Phase II time step convergence study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Δt (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.125</td>
</tr>
</tbody>
</table>

The simulation results did not converge monotonically, so the same general procedure used for the grid dependency study was followed to quantify the level of uncertainty from the time step size used for transient simulations. Changing from a time step size of 0.25 to 0.125 s yielded integral differences of 9.37%, 7.94%, and 7.31%, respectively, for global average concentration, and maximum and average concentrations at the measurement plane located 0.15 m (6 in.) above the slotted floor (Table 6.10). Therefore, a time step size of 0.25 seconds was selected for use in the Phase II simulations.
Table 6.10 Difference (%) between subsequent time steps for the Phase II time step convergence study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Δt (s)</th>
<th>Integrated Global C_{avg}</th>
<th>Difference Integrated Global C_{avg}</th>
<th>Integrated Planar C_{max}</th>
<th>Difference Integrated Planar C_{max}</th>
<th>Integrated Planar C_{avg}</th>
<th>Difference Integrated Planar C_{avg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>874.2</td>
<td>-</td>
<td>5,842.0</td>
<td>-</td>
<td>396.8</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1,100.1</td>
<td>22.88</td>
<td>6,482.4</td>
<td>10.39</td>
<td>531.3</td>
<td>28.99</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>1,305.5</td>
<td>17.08</td>
<td>7,481.3</td>
<td>14.31</td>
<td>629.6</td>
<td>16.94</td>
</tr>
<tr>
<td>4</td>
<td>0.125</td>
<td>1,433.8</td>
<td>9.37</td>
<td>8,099.7</td>
<td>7.94</td>
<td>677.4</td>
<td>7.31</td>
</tr>
</tbody>
</table>

Note: Difference (%) is a comparison between the current and previous value, where Difference (%) = \(|\text{Previous} - \text{Current}| / \left[ \frac{\text{Previous} + \text{Current}}{2} \right] \) * 100

6.3 Results

The data analysis procedures and tunnel ventilated barn simulation results are presented in this section. The “measurement plane” in the barn refers to the plane located 0.15 m (6 in.) above the slotted floor. The term “contaminated” is used to describe the conditions in the barn airspace have a H$_2$S concentration ≥ 50 ppm. For this study, the barn airspace was considered to be contaminated when the concentration on the measurement plane became contaminated. This is because for gas to enter the barn airspace from the manure pit, it must pass through the measurement plane.

The criteria used to compare simulation cases with different pit-safety ventilation fan locations and flow rates were: percent area on the barn measurement plane where the H$_2$S concentration was 50 ppm or greater, the total duration of time when C(H$_2$S) was 50 ppm or greater, the maximum H$_2$S concentration in the barn overall and within each quintile, and the time required to reach 10 or 1 ppm anywhere inside the manure pit (T_{pel}(10) and T_{pel}(1), respectively).
6.3.1 Barn quintiles

The barn was divided into five 6.10 m (20 ft) long quintiles for analysis (Figure 6.12). This was done to determine if the H$_2$S concentration in one or more quintiles never reached a level of 50 ppm for 10 minutes or more during manure pit-safety ventilation, then that quintile might be considered “safe” for occupation by animals if they could be corralled into that region of the barn. This might be achievable in barns with multiple pens where pen dividers could be used to exclude animals from regions where H$_2$S gas contamination was present. Division into quintiles also allows for finer quantitative comparisons than considering only the contaminated area of the entire barn. In addition to comparing the total barn area with a contaminant gas concentration $\geq$ 50 ppm, it is possible to examine the area within each quintile with a contaminant gas concentration $\geq$ 50 ppm for each simulation case. One quintile contains 200 of the 1,000 total grid points on the barn measurement plane.

![Barn Exhaust Fan](image)

Figure 6.12. Pit-safety fan locations and barn quintiles for tunnel ventilated barn cases.
6.3.2 Barn measurement plane calculations

To determine the percentage of the area with a contaminant gas concentration ≥ 50 ppm at every output time step, point parameters were located at 1,000 points spaced evenly across the measurement plane located 0.15 m (6 in.) above the barn floor (Figure 6.13). Each point represented an area of 0.37 m\(^2\) (4 ft\(^2\)).

![Figure 6.13. Point parameter locations on a plane located 0.15 m (6 in.) above the barn floor.](image)

The percentage of the area with a concentration ≥ 50 ppm was determined by dividing the number of points with a concentration ≥ 50 ppm by the total number of points (Equation 6-1).

\[
Percent \geq 50\ ppm = \frac{\sum_{n} C_{n} > 50\ ppm}{n} \times 100\%
\]

Where:

- \(n\) = number of points
- \(C_{n}\) = concentration at point location (n)

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The maximum H$_2$S concentration of all 1,000 points (or 200 points in each quintile) and the total time the maximum value was $\geq$ 50 ppm during the first 300s of ventilation were also extracted and reported.

### 6.3.3 Composite contamination maps

Composite plots were created to graphically show the contaminated areas of the barn during the first 300s of ventilation so comparisons could be made across all simulated fan locations and flow rates. These plots incorporated the transient results for different initial concentrations by evaluating the H$_2$S concentration “history” at each of the 1,000 grid points on the measurement plane located 0.15 m (6 in.) above the barn floor. On the plots, the grid points were replaced with squares representing a 0.61 m × 0.61 m (2 ft × 2 ft) area. If the concentration at an individual grid point reached or exceeded 50 ppm during the first 300s of ventilation, the square was marked with a value of 1 and colored purple to indicate a contaminated area. If the concentration remained below 50 ppm, the square was marked with a value of 0 and colored white to indicate the area was clear.

Figure 6.14 shows five individual plots of contaminated area in the barn on the measurement plane located 0.15 m (6 in.) above the floor for initial pit H$_2$S concentrations from 100 to 500 ppm for the simulation case TV32Qr30. It is clear from the plots that as the initial concentration increases, the contaminated area in the barn also increases. Figure 6.15 shows the resulting combined plot which illustrates the additional contaminated area for each 100 ppm increase in initial H$_2$S concentration inside the manure pit. In the combined plot, additional colors were used to indicate the initial pit concentration. Darker colors indicate additional areas of the barn that become contaminated at higher initial pit H$_2$S concentrations. These plots can be used with the tabular data to evaluate which quintiles of the barn need to be evacuated during manure pit-safety ventilation events. For example, Table 6.11 lists the maximum concentration
reached in the entire barn and in each quintile during manure pit and barn ventilation for different initial manure pit H$_2$S concentrations from 100 to 500 ppm for simulation case TV32Qr30.

Figure 6.15 shows some contaminated area in quintile IV for an initial H$_2$S concentration inside the manure pit equal to 100 ppm. However, Table 6.11 lists the maximum concentration in quintile IV was only 73 ppm, which is lower than the IDLH concentration.
Figure 6.14. Individual plots showing contaminated area in the barn on the measurement plane for (a) $C_0 = 100$, (b) 200, (c) 300, (d) 400, and (e) 500 ppm for case TV32Qr30.
Figure 6.15. Combined plot showing contaminated area in the barn on the measurement plane for $C_0 = 100, 200, 300, 400,$ and $500$ ppm for case TV32Qr30.

Table 6.11. Maximum $H_2S$ concentration in each quintile during pit and barn ventilation for simulation case TV32Qr30.

<table>
<thead>
<tr>
<th>TV32 Qr30</th>
<th>Max C in each Quintile (ppm)</th>
<th>For first 300s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_0$ (ppm)</td>
<td>Overall</td>
<td>V</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>
6.3.4 Tunnel ventilated barn simulation results

This section presents the TV barn simulation results for each simulation case. General discussion for all TV barn simulation cases follows in section 6.4.

All simulations started with the same initial conditions. At time \( t = 0 \), the barn airspace was full of atmospheric air (this included the open space in the porous media used to represent the slotted floor), and a uniform initial concentration of \( \text{H}_2\text{S} \) gas filled the airspace inside the manure pit up to the bottom of the slotted floor. At time \( t = 0^+ \), the barn exhaust fans and manure pit-safety ventilation fan (used for all cases except the No Pit Fan case) were operating.

Cut plots for each simulation case illustrate the air flow pattern and gas concentration profile through the barn and manure pit during ventilation. Air entered the barn through the opening at the inlet end, and was drawn through the length of the barn before being exhausted by the barn ventilation fans in the outlet end wall. In general, air moved in a straight path through the barn airspace at the design velocity of 3.0 m/s (10.0 ft/s). The flow pattern changed at low elevations above the slotted floor. The pit-safety ventilation fan forced fresh air into the manure pit, and some air flowed through the manure pit as a result of air movement created by the barn exhaust fans. The air flow in the manure pit airspace was relatively slow away from the pit-safety fan location, where the velocity was less than 0.4 m/s (1.3 ft/s), and large recirculation zones were present in most cases. Figure 6.16 shows the location of the vertical cross section planes used for cut plots in this section.
Plane A is located at \( Y = +4.9 \text{ m} (+16.0 \text{ ft.}) \)

Plane B is located at \( Y = 0.0 \text{ m} (0.0 \text{ ft.}) \)

Plane C is located at \( Y = -4.9 \text{ m} (-16.0 \text{ ft.}) \)

Figure 6.16. Schematic of the tunnel ventilated barn showing the location of the planes used for vertical cut plots.

### 6.3.4.1 No pit fan

A simulation case with no pit-safety ventilation fan was used as a baseline for comparisons against other fan location and flow rates. In this configuration, the tunnel barn exhaust fans were the only source of ventilation air flow. Since there was no pit-safety ventilation fan, \( \text{H}_2\text{S} \) gas from the manure pit began to mix with the atmospheric air entering the inlet end of the barn. \( \text{H}_2\text{S} \) gas exiting the manure pit was carried up into the barn airspace then removed from the barn by the exhaust fans at the outlet end of the barn. Figure 6.17 illustrates the air flow pattern through the barn and manure pit during ventilation. Figure 6.18 shows the vertical \( \text{H}_2\text{S} \) gas distribution profiles at three section planes at time = 5s when the 50 ppm contour reached a maximum height above the barn floor for an initial manure pit \( \text{H}_2\text{S} \) concentration of 100 ppm.
Figure 6.17. Vertical cut plots through the tunnel ventilated barn showing velocity vectors and recirculation zones when time = 300s for the simulation case with no pit fan.
Figure 6.18. Vertical cut plots through the tunnel ventilated barn showing the \( \text{H}_2\text{S} \) gas concentration profile in the barn airspace 5s after the start of barn ventilation for the simulation case with no pit fan for an initial manure pit \( \text{H}_2\text{S} \) concentration of 100 ppm.
Figure 6.19 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn ventilation with initial manure pit H$_2$S concentrations equal to 100, 200, 300, 400, and 500 ppm for the case with no pit-safety ventilation fan. Table 6.12 lists comparison statistics for the simulation case with no pit-safety ventilation fan for several initial manure pit concentration values. The statistics include the percentage of contaminated area where C(H$_2$S) ≥ 50 ppm, duration of time when C(H$_2$S) ≥ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of time required to reach a maximum H$_2$S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.

![Color Legend]

<table>
<thead>
<tr>
<th>Color Legend</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear (&lt; 50 ppm)</td>
<td>C$_0$ = 100 ppm</td>
</tr>
<tr>
<td>C$_0$ = 200 ppm</td>
<td></td>
</tr>
<tr>
<td>C$_0$ = 300 ppm</td>
<td></td>
</tr>
<tr>
<td>C$_0$ = 400 ppm</td>
<td></td>
</tr>
<tr>
<td>C$_0$ = 500 ppm</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.19. Plot showing contaminated areas on the TV barn measurement plane during barn ventilation for the case with no pit fan.
Table 6.12. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn ventilation for the No Pit Fan TV case with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %$^a$</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>724 s$^d$</td>
<td>1,052 s$^e$</td>
</tr>
<tr>
<td></td>
<td>8 s$^b$</td>
<td>8 s</td>
<td>0 s</td>
<td>0 s</td>
<td>11 ppm</td>
<td>16 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ppm</td>
<td>36 ppm</td>
<td>4 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>41 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>725 s$^d$</td>
<td>1,056 s$^e$</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>17 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>36 ppm</td>
<td>4 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>74 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>732 s$^d$</td>
<td>1,066 s$^e$</td>
</tr>
<tr>
<td></td>
<td>16 s</td>
<td>16 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>18 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>39 ppm</td>
<td>5 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>20 %</td>
<td>100 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>757 s$^d$</td>
<td>1,104 s$^e$</td>
</tr>
<tr>
<td></td>
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<td>40 s</td>
<td>2 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>53 ppm</td>
<td>7 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>22 %</td>
<td>100 %</td>
<td>11 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>783 s$^d$</td>
<td>1,135 s$^e$</td>
</tr>
<tr>
<td></td>
<td>50 s</td>
<td>50 s</td>
<td>4 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>71 ppm</td>
<td>9 ppm</td>
<td>22 ppm</td>
<td>33 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>32 %</td>
<td>100 %</td>
<td>30 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>882 s$^d$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>80 s</td>
<td>7 s</td>
<td>0 s</td>
<td>0 s</td>
<td>130 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>142 ppm</td>
<td>18 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>48 %</td>
<td>100 %</td>
<td>34 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>962 s$^d$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>240 s</td>
<td>100 s</td>
<td>8 s</td>
<td>0 s</td>
<td>19 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>214 ppm</td>
<td>26 ppm</td>
<td>67 ppm</td>
<td>98 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>55 %</td>
<td>100 %</td>
<td>42 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1,016 s$^d$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>280 s</td>
<td>120 s</td>
<td>9 s</td>
<td>0 s</td>
<td>46 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>285 ppm</td>
<td>35 ppm</td>
<td>89 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>60 %</td>
<td>100 %</td>
<td>43 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1,052 s$^d$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>140 s</td>
<td>9 s</td>
<td>0 s</td>
<td>65 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>356 ppm</td>
<td>44 ppm</td>
<td>111 ppm</td>
<td>164 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: “-“ indicates that the simulation ended before $T_{pel}$ was reached.
The following were observed for the simulation case with no pit fan:

1. Quintiles I, II, III, and IV were always clear when $C_0 \leq 55$ ppm inside the manure pit.
2. Quintile I was not contaminated when $C_0 \leq 100$ ppm.
3. Quintile II was not contaminated when $C_0 \leq 200$ ppm.
4. Quintile III was the only quintile that was always clear with $C(H_2S) \leq 50$ ppm and also had the lowest maximum concentration on the 0.15 m (6 in.) barn measurement plane for all $C_0$ values ranging from 50 to 500 ppm.
5. Quintile IV was only 1% contaminated when $C_0 = 75$ ppm.
6. Quintile V was never completely clear, even when $C_0 = 50$ ppm. This was because the concentration of $H_2S$ gas on the 0.15 m (6 in.) plane after leaving the manure pit was always greatest at the outlet end of the barn for the case with no pit fan.
7. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 75$ ppm inside the manure pit, and was 74% contaminated when $C_0 = 55$ ppm.

**6.3.4.2 TV11**

Simulation cases for pit-safety fan location (1,1) were performed using $Q_{ratio}$ of 30, 60, and 120. Figure 6.20 illustrates the air flow pattern through the barn and manure pit during ventilation for $Q_{r30}$. Figure 6.21 shows the vertical $H_2S$ gas distribution profiles at three section planes at time $= 5s$ when the 50 ppm contour reached a maximum height above the barn floor for an initial manure pit $H_2S$ concentration of 100 ppm.
Figure 6.20. Vertical cut plots through the tunnel ventilated barn showing velocity vectors and recirculation zones when time = 300s for simulation case TV11Qr30.
Figure 6.21. Vertical cut plots through the tunnel ventilated barn showing the H₂S gas concentration profile in the barn airspace 5s after the start of barn ventilation for simulation case TV11Qr30 for an initial manure pit H₂S concentration of 100 ppm.
Figure 6.22 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation with initial manure pit H$_2$S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (1,1) and Q$_{ratio}$ 30, 60, and 120. Table 6.13, Table 6.14, and Table 6.15 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (1,1) and Q$_{ratio}$ 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H$_2$S) $\geq$ 50 ppm, duration of time when C(H$_2$S) $\geq$ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H$_2$S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.
Figure 6.22. Plot showing contaminated areas on the TV barn measurement plane during barn and pit-safety ventilation for case TV11.
Table 6.13. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV11Qr30 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1% $^a$</td>
<td>4%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0s</td>
<td>736 s $^d$</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>40%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0s</th>
<th>738 s $^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>16%</td>
<td>78%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0s</td>
<td>745 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>75</th>
<th>22%</th>
<th>100%</th>
<th>10%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0s</th>
<th>790 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>24%</td>
<td>100%</td>
<td>21%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0s</td>
<td>850 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>34%</th>
<th>100%</th>
<th>35%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0s</th>
<th>978 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>50%</td>
<td>100%</td>
<td>44%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0s</td>
<td>1,034 s</td>
</tr>
<tr>
<td>-------------</td>
<td>---------</td>
<td>-----</td>
<td>----</td>
<td>-----</td>
<td>----</td>
<td>----</td>
<td>---------------</td>
<td>--------------</td>
</tr>
<tr>
<td>400</td>
<td>57%</td>
<td>100%</td>
<td>48%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0s</td>
<td>1,088 s</td>
</tr>
<tr>
<td>-------------</td>
<td>---------</td>
<td>-----</td>
<td>----</td>
<td>-----</td>
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<td>----</td>
<td>---------------</td>
<td>--------------</td>
</tr>
<tr>
<td>500</td>
<td>63%</td>
<td>100%</td>
<td>53%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0s</td>
<td>1,126 s</td>
</tr>
</tbody>
</table>

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.14. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV11Qr60 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel(10)}$</th>
<th>$T_{pel(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %</td>
<td>4 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 s</td>
<td>16 ppm</td>
</tr>
<tr>
<td></td>
<td>8 s</td>
<td>8 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>13 ppm</td>
<td>0 s</td>
<td>16 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>40 ppm</td>
<td>5 ppm</td>
<td>5 ppm</td>
<td>13 ppm</td>
<td>0 s</td>
<td>16 ppm</td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>39 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 s</td>
<td>16 ppm</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>14 ppm</td>
<td>0 s</td>
<td>16 ppm</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>41 ppm</td>
<td>5 ppm</td>
<td>5 ppm</td>
<td>14 ppm</td>
<td>0 s</td>
<td>16 ppm</td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>76 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 s</td>
<td>17 ppm</td>
</tr>
<tr>
<td></td>
<td>18 s</td>
<td>18 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>15 ppm</td>
<td>0 s</td>
<td>17 ppm</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>44 ppm</td>
<td>6 ppm</td>
<td>6 ppm</td>
<td>15 ppm</td>
<td>0 s</td>
<td>17 ppm</td>
</tr>
<tr>
<td>75</td>
<td>21 %</td>
<td>100 %</td>
<td>3 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 s</td>
<td>24 ppm</td>
</tr>
<tr>
<td></td>
<td>25 s</td>
<td>25 s</td>
<td>4 s</td>
<td>0 s</td>
<td>0 s</td>
<td>20 ppm</td>
<td>0 s</td>
<td>24 ppm</td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>61 ppm</td>
<td>8 ppm</td>
<td>8 ppm</td>
<td>20 ppm</td>
<td>0 s</td>
<td>24 ppm</td>
</tr>
<tr>
<td>100</td>
<td>23 %</td>
<td>100 %</td>
<td>15 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 s</td>
<td>32 ppm</td>
</tr>
<tr>
<td></td>
<td>30 s</td>
<td>30 s</td>
<td>6 s</td>
<td>0 s</td>
<td>0 s</td>
<td>26 ppm</td>
<td>0 s</td>
<td>32 ppm</td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>81 ppm</td>
<td>11 ppm</td>
<td>11 ppm</td>
<td>26 ppm</td>
<td>0 s</td>
<td>32 ppm</td>
</tr>
<tr>
<td>200</td>
<td>34 %</td>
<td>100 %</td>
<td>31 %</td>
<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
<td>0 s</td>
<td>63 ppm</td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>70 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>20 s</td>
<td>0 s</td>
<td>63 ppm</td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>161 ppm</td>
<td>21 ppm</td>
<td>21 ppm</td>
<td>20 s</td>
<td>0 s</td>
<td>63 ppm</td>
</tr>
<tr>
<td>300</td>
<td>50 %</td>
<td>100 %</td>
<td>41 %</td>
<td>0 %</td>
<td>24 %</td>
<td>87 %</td>
<td>0 s</td>
<td>95 ppm</td>
</tr>
<tr>
<td></td>
<td>240 s</td>
<td>100 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>110 s</td>
<td>0 s</td>
<td>95 ppm</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>242 ppm</td>
<td>32 ppm</td>
<td>32 ppm</td>
<td>79 ppm</td>
<td>0 s</td>
<td>95 ppm</td>
</tr>
<tr>
<td>400</td>
<td>56 %</td>
<td>100 %</td>
<td>43 %</td>
<td>0 %</td>
<td>47 %</td>
<td>89 %</td>
<td>0 s</td>
<td>126 ppm</td>
</tr>
<tr>
<td></td>
<td>270 s</td>
<td>110 s</td>
<td>10 s</td>
<td>0 s</td>
<td>195 s</td>
<td>256 s</td>
<td>0 s</td>
<td>126 ppm</td>
</tr>
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<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>323 ppm</td>
<td>42 ppm</td>
<td>42 ppm</td>
<td>106 ppm</td>
<td>0 s</td>
<td>126 ppm</td>
</tr>
<tr>
<td>500</td>
<td>62 %</td>
<td>100 %</td>
<td>47 %</td>
<td>1 %</td>
<td>70 %</td>
<td>92 %</td>
<td>0 s</td>
<td>158 ppm</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>120 s</td>
<td>10 s</td>
<td>20 s</td>
<td>260 s</td>
<td>291 s</td>
<td>0 s</td>
<td>158 ppm</td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>404 ppm</td>
<td>53 ppm</td>
<td>53 ppm</td>
<td>132 ppm</td>
<td>0 s</td>
<td>158 ppm</td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.

b. Duration of time with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.

c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.

d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.

e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: “-“ indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.15. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV11Qr120 with $T_{pel}$ values.

<table>
<thead>
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<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel(10)}$</th>
<th>$T_{pel(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 %$^a$</td>
<td>4%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>715 s$^d$</td>
</tr>
<tr>
<td></td>
<td>8 s$^b$</td>
<td>8</td>
<td>0</td>
<td>0 s</td>
<td>5 ppm</td>
<td>12 ppm</td>
<td>17 ppm</td>
<td>1,055 s$^e$</td>
</tr>
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<td>50 ppm</td>
<td>38 ppm</td>
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<td>17 ppm</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>717 s$^d$</td>
</tr>
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<td></td>
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<td>0</td>
<td>0 s</td>
<td>5 ppm</td>
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<td>17 ppm</td>
<td>1,057 s$^e$</td>
</tr>
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<td>51 ppm</td>
<td>39 ppm</td>
<td>5 ppm</td>
<td>12 ppm</td>
<td>17 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15%</td>
<td>74%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>723 s$^d$</td>
</tr>
<tr>
<td></td>
<td>16 s</td>
<td>16</td>
<td>0</td>
<td>0 s</td>
<td>5 ppm</td>
<td>13 ppm</td>
<td>18 ppm</td>
<td>1,064 s$^e$</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>42 ppm</td>
<td>5 ppm</td>
<td>13 ppm</td>
<td>18 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>100%</td>
<td>2%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>765 s$^d$</td>
</tr>
<tr>
<td></td>
<td>25 s</td>
<td>25</td>
<td>3</td>
<td>0 s</td>
<td>7 ppm</td>
<td>18 ppm</td>
<td>25 ppm</td>
<td>1,114 s$^e$</td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>57 ppm</td>
<td>7 ppm</td>
<td>18 ppm</td>
<td>25 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>22%</td>
<td>100%</td>
<td>11%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>825 s$^d$</td>
</tr>
<tr>
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<td>50</td>
<td>5</td>
<td>0 s</td>
<td>10 ppm</td>
<td>24 ppm</td>
<td>33 ppm</td>
<td>1,151 s$^e$</td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>76 ppm</td>
<td>10 ppm</td>
<td>24 ppm</td>
<td>33 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>33%</td>
<td>100%</td>
<td>31%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>951 s$^d$</td>
</tr>
<tr>
<td></td>
<td>170 s</td>
<td>70</td>
<td>7</td>
<td>0 s</td>
<td>20 ppm</td>
<td>48 ppm</td>
<td>66 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>152 ppm</td>
<td>20 ppm</td>
<td>48 ppm</td>
<td>66 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>49%</td>
<td>100%</td>
<td>41%</td>
<td>0%</td>
<td>17%</td>
<td>88%</td>
<td>99%</td>
<td>987 s$^d$</td>
</tr>
<tr>
<td></td>
<td>240 s</td>
<td>90</td>
<td>9</td>
<td>0 s</td>
<td>30 ppm</td>
<td>72 ppm</td>
<td>99 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>228 ppm</td>
<td>30 ppm</td>
<td>72 ppm</td>
<td>99 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>54%</td>
<td>100%</td>
<td>42%</td>
<td>0%</td>
<td>40%</td>
<td>89%</td>
<td>92%</td>
<td>1,024 s$^d$</td>
</tr>
<tr>
<td></td>
<td>270 s</td>
<td>100</td>
<td>9</td>
<td>0 s</td>
<td>40 ppm</td>
<td>96 ppm</td>
<td>132 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>304 ppm</td>
<td>40 ppm</td>
<td>96 ppm</td>
<td>132 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60%</td>
<td>100%</td>
<td>45%</td>
<td>0%</td>
<td>65%</td>
<td>92%</td>
<td>99%</td>
<td>1,055 s$^d$</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>120</td>
<td>9</td>
<td>0 s</td>
<td>65 ppm</td>
<td>92 ppm</td>
<td>92 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>380 ppm</td>
<td>50 ppm</td>
<td>120 ppm</td>
<td>165 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: “-” indicates that the simulation ended before $T_{pel}$ was reached.
The following were observed for simulation case TV11:

1. Quintiles I, II, III, and IV were always clear when $C_0 \leq 55$ ppm inside the manure pit.
2. Quintile I was not contaminated when $C_0 \leq 100$ ppm for all three $Q_{ratios}$.
3. Quintile II was not contaminated when $C_0 \leq 100$ ppm for $Q_{r30}$ and $Q_{r60}$, and when $C_0 \leq 200$ ppm for $Q_{r120}$.
4. Quintile III was the only quintile that was always clear for all $C_0$ values ranging from 50 to 500 ppm with $C(H_2S) \leq 50$ ppm for $Q_{r30}$ and $Q_{r120}$. Quintile III had only 1% contaminated area for $Q_{r60}$ when $C_0 = 500$ ppm. Quintile III had the lowest maximum concentration on the 0.15 m (6 in.) measurement plane of any quintile for all $C_0$ values ranging from 50 to 500 ppm.
5. Quintile IV was only 10%, 3%, and 2% contaminated when $C_0 = 75$ ppm for $Q_{r30}$, $Q_{r60}$, and $Q_{r120}$, respectively.
6. Quintile V was never completely clear, even when $C_0 = 50$ ppm. This was because the concentration of $H_2S$ gas on the 0.15 m (6 in.) plane after leaving the manure pit was always greatest at the at the outlet end of the barn for case TV11.
7. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 75$ ppm inside the manure pit for all three $Q_{ratios}$, and was 78%, 76%, and 74% contaminated when $C_0 = 55$ ppm for $Q_{r30}$, $Q_{r60}$, and $Q_{r120}$, respectively.

6.3.4.3 TV12

Simulation cases for pit-safety fan location (1,2) were performed using $Q_{ratios}$ of 8, 15, 30, 60, and 120. Figure 6.23 illustrates the air flow pattern through the barn and manure pit during ventilation for $Q_{r30}$. Figure 6.24 shows the vertical $H_2S$ gas distribution profiles at three section planes at time = 5s when the 50 ppm contour reached a maximum height above the barn floor for an initial manure pit $H_2S$ concentration of 100 ppm.
Figure 6.23. Vertical cut plots through the tunnel ventilated barn showing velocity vectors and recirculation zones when time = 300s for simulation case TV12Qr30.
Figure 6.24. Vertical cut plots through the tunnel ventilated barn showing the H$_2$S gas concentration profile in the barn airspace 5s after the start of barn ventilation for simulation case TV12Qr30 for an initial manure pit H$_2$S concentration of 100 ppm.
Figure 6.25 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor resulting from barn and pit-safety ventilation with initial manure pit \( \text{H}_2\text{S} \) concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (1,2) and \( Q_{\text{ratios}} \) 30, 60, and 120. Figure 6.26 shows two additional simulation cases for \( Q_{\text{ratios}} \) 8 and 15. Table 6.16, Table 6.17, and Table 6.18 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (1,2) and \( Q_{\text{ratios}} \) 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where \( \text{C(H}_2\text{S)} \geq 50 \text{ ppm} \), duration of time when \( \text{C(H}_2\text{S)} \geq 50 \text{ ppm} \), and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum \( \text{H}_2\text{S} \) concentration of 10 or 1 ppm anywhere inside the manure pit airspace. Table 6.19 and Table 6.20 list the comparison statistics for additional \( Q_{\text{ratios}} \) 8 and 15, respectively.
Figure 6.25. Plot showing contaminated areas on the TV barn measurement plane during barn and pit-safety ventilation for case TV12.
Table 6.16. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV12Qr30 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %$^a$</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>742 s$^d$</td>
<td>1,086 s$^e$</td>
</tr>
<tr>
<td></td>
<td>6 s$^b$</td>
<td>6 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>744 s</td>
<td>1,090 s</td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>50 ppm</td>
<td>42 ppm</td>
<td>5 ppm</td>
<td>12 ppm</td>
<td>17 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>41 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>755 s</td>
<td>1,100 s</td>
</tr>
<tr>
<td></td>
<td>10 s</td>
<td>10 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>793 s</td>
<td>1,139 s</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>43 ppm</td>
<td>5 ppm</td>
<td>12 ppm</td>
<td>17 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>16 %</td>
<td>81 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>755 s</td>
<td>1,174 s</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>850 s</td>
<td>1,174 s</td>
</tr>
<tr>
<td></td>
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<td>55 ppm</td>
<td>46 ppm</td>
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<td>13 ppm</td>
<td>18 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>22 %</td>
<td>100 %</td>
<td>10 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>953 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>18 s</td>
<td>18 s</td>
<td>5 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>130 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>63 ppm</td>
<td>8 ppm</td>
<td>18 ppm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>24 %</td>
<td>100 %</td>
<td>20 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1,015 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>20 s</td>
<td>6 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>87 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>84 ppm</td>
<td>10 ppm</td>
<td>24 ppm</td>
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</tr>
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<td>200</td>
<td>34 %</td>
<td>100 %</td>
<td>33 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1,050 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>50 s</td>
<td>10 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>99 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>167 ppm</td>
<td>21 ppm</td>
<td>49 ppm</td>
<td>66 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>50 %</td>
<td>100 %</td>
<td>41 %</td>
<td>0 %</td>
<td>24 %</td>
<td>87 %</td>
<td>1,015 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>230 s</td>
<td>70 s</td>
<td>12 s</td>
<td>0 s</td>
<td>130 s</td>
<td>210 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>251 ppm</td>
<td>31 ppm</td>
<td>73 ppm</td>
<td>100 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>59 %</td>
<td>100 %</td>
<td>51 %</td>
<td>0 %</td>
<td>54 %</td>
<td>89 %</td>
<td>1,050 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>290 s</td>
<td>80 s</td>
<td>12 s</td>
<td>0 s</td>
<td>185 s</td>
<td>276 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>335 ppm</td>
<td>42 ppm</td>
<td>98 ppm</td>
<td>133 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>64 %</td>
<td>100 %</td>
<td>52 %</td>
<td>1 %</td>
<td>76 %</td>
<td>92 %</td>
<td>1,086 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>100 s</td>
<td>12 s</td>
<td>10 s</td>
<td>245 s</td>
<td>291 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>418 ppm</td>
<td>52 ppm</td>
<td>122 ppm</td>
<td>166 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.

b. Duration of time with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.

c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.

d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.

e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.17. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV12Qr60 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel(10)}$</th>
<th>$T_{pel(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %(^a)</td>
<td>6 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>737 s(^d)</td>
</tr>
<tr>
<td></td>
<td>8 s(^b)</td>
<td>8 s</td>
<td>39 ppm</td>
<td>5 ppm</td>
<td>13 ppm</td>
<td>17 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ppm(^c)</td>
<td>50 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>40 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>738 s(^d)</td>
<td>1,054 s(^e)</td>
</tr>
<tr>
<td></td>
<td>10 s</td>
<td>10 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>40 ppm</td>
<td>13 ppm</td>
<td>17 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>74 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>764 s(^d)</td>
<td>1,064 s(^e)</td>
</tr>
<tr>
<td></td>
<td>14 s</td>
<td>14 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>43 ppm</td>
<td>14 ppm</td>
<td>19 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>20 %</td>
<td>100 %</td>
<td>2 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>820 s(^d)</td>
<td>1,123 s(^e)</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>20 s</td>
<td>3 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>58 ppm</td>
<td>19 ppm</td>
<td>25 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>23 %</td>
<td>100 %</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>881 s(^d)</td>
<td>1,184 s(^e)</td>
</tr>
<tr>
<td></td>
<td>30 s</td>
<td>30 s</td>
<td>5 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>78 ppm</td>
<td>25 ppm</td>
<td>34 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>34 %</td>
<td>100 %</td>
<td>31 %</td>
<td>0 %</td>
<td>1 %</td>
<td>41 %</td>
<td>970 s(^d)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>60 s</td>
<td>8 s</td>
<td>0 s</td>
<td>10 s</td>
<td>130 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>155 ppm</td>
<td>50 ppm</td>
<td>68 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>50 %</td>
<td>100 %</td>
<td>41 %</td>
<td>0 %</td>
<td>20 %</td>
<td>87 %</td>
<td>998 s(^d)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>240 s</td>
<td>80 s</td>
<td>9 s</td>
<td>0 s</td>
<td>120 s</td>
<td>220 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>233 ppm</td>
<td>31 ppm</td>
<td>75 ppm</td>
<td>101 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>56 %</td>
<td>100 %</td>
<td>42 %</td>
<td>0 %</td>
<td>49 %</td>
<td>89 %</td>
<td>1,027 s(^d)</td>
<td>-</td>
</tr>
<tr>
<td></td>
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<td>90 s</td>
<td>10 s</td>
<td>0 s</td>
<td>175 s</td>
<td>266 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>311 ppm</td>
<td>42 ppm</td>
<td>101 ppm</td>
<td>135 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>63 %</td>
<td>100 %</td>
<td>48 %</td>
<td>2 %</td>
<td>74 %</td>
<td>92 %</td>
<td>1,053 s(^d)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>100 s</td>
<td>10 s</td>
<td>0 s</td>
<td>220 s</td>
<td>290 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>388 ppm</td>
<td>52 ppm</td>
<td>126 ppm</td>
<td>169 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(a\). Percent of area with $H_2S$ concentration $\geq 50$ ppm during the first 300s of pit and barn ventilation.

\(b\). Duration of time with $H_2S$ concentration $\geq 50$ ppm during the first 300s of pit and barn ventilation.

\(c\). Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.

\(d\). Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.

\(e\). Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: “-” indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.18. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV12Qr120 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %$^a$</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>701 s$^d$</td>
<td>1,022 s$^e$</td>
</tr>
<tr>
<td></td>
<td>8 s$^b$</td>
<td>8 s</td>
<td>37 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>17 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 ppm$^c$</td>
<td>50 ppm</td>
<td></td>
<td>5 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>7 %</td>
<td>37 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>706 s</td>
<td>1,024 s</td>
</tr>
<tr>
<td></td>
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<td>12 s</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td></td>
<td>5 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>75 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>720 s</td>
<td>1,035 s</td>
</tr>
<tr>
<td></td>
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<td>16 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55 ppm</td>
<td></td>
<td>6 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>20 %</td>
<td>100 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>762 s</td>
<td>1,092 s</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>20 s</td>
<td>3 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75 ppm</td>
<td></td>
<td>8 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>22 %</td>
<td>100 %</td>
<td>11 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>802 s</td>
<td>1,159 s</td>
</tr>
<tr>
<td></td>
<td>40 s</td>
<td>40 s</td>
<td>5 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td></td>
<td>10 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>33 %</td>
<td>100 %</td>
<td>31 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>924 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>70 s</td>
<td>7 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td></td>
<td>20 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>49 %</td>
<td>100 %</td>
<td>41 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>976 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>230 s</td>
<td>90 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td></td>
<td>31 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>55 %</td>
<td>100 %</td>
<td>42 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>999 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>270 s</td>
<td>100 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td></td>
<td>41 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>62 %</td>
<td>100 %</td>
<td>44 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1,022 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>120 s</td>
<td>9 s</td>
<td>10 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td></td>
<td>51 ppm</td>
<td>10 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
The following were observed for simulation case TV12 (Qr30, Qr60, Qr120):

1. Quintile V was never completely clear, even when $C_0 = 50$ ppm. This was because the concentration of $H_2S$ gas on the 0.15 m (6 in.) plane after leaving the manure pit was always greatest at the at the outlet end of the barn for the case with no pit fan.

2. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 75$ ppm inside the manure pit for all three $Q_{ratio}$s, and was 81%, 74%, and 75% contaminated when $C_0 = 55$ ppm for Qr30, Qr60, and Qr120, respectively.

3. Quintiles I, II, III, and IV were always clear when $C_0 \leq 55$ ppm inside the manure pit. Quintile IV was only 10%, 2%, and 1% contaminated when $C_0 = 75$ ppm for Qr30, Qr60, and Qr120, respectively.

4. Quintile III was the only quintile that was always clear for all $C_0$ values ranging from 50 to 500 ppm with $C(H_2S) \leq 50$ ppm for Qr30 and Qr120. Quintile III was only 2% contaminated for Qr60 when $C_0 = 500$ ppm. Quintile III had the lowest maximum concentration on the 0.15 m (6 in.) measurement plane of any quintile for all $C_0$ values ranging from 50 to 500 ppm.

5. Quintile II was not contaminated when $C_0 \leq 200$ ppm for Qr30 and Qr120, and when $C_0 \leq 100$ ppm for Qr60.

6. Quintile I was not contaminated when $C_0 \leq 100$ ppm for all three $Q_{ratio}$s.
Figure 6.26. Plot showing contaminated areas on the TV barn measurement plane during barn and pit-safety ventilation for additional fan cases TV12 Qr8 and Qr15.
Table 6.19. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV12Qr8 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2 %$^a$</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>882 s</td>
</tr>
<tr>
<td></td>
<td>4 s$^b$</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>12</td>
<td>0 s</td>
<td>1,319 s</td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>50</td>
<td>49 ppm</td>
<td>8 ppm</td>
<td>0</td>
<td>17</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>7 %</td>
<td>33</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>888 s</td>
</tr>
<tr>
<td></td>
<td>8 s</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>1,324 s</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51</td>
<td>50 ppm</td>
<td>8 ppm</td>
<td>0</td>
<td>18</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>21 %</td>
<td>90</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>914 s</td>
</tr>
<tr>
<td></td>
<td>10 s</td>
<td>10</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>1,342 s</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55</td>
<td>54 ppm</td>
<td>9 ppm</td>
<td>0</td>
<td>19</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>28 %</td>
<td>99</td>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>996 s</td>
</tr>
<tr>
<td></td>
<td>16 s</td>
<td>16</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>1,441 s</td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75</td>
<td>74 ppm</td>
<td>12 ppm</td>
<td>0</td>
<td>26</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>30 %</td>
<td>100</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>1,039 s</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>20</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>1,515 s</td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>99 ppm</td>
<td>16 ppm</td>
<td>0</td>
<td>35</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>41 %</td>
<td>100</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>1,184 s</td>
</tr>
<tr>
<td></td>
<td>180 s</td>
<td>60</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 s</td>
<td>1,664 s</td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>198 ppm</td>
<td>32 ppm</td>
<td>0</td>
<td>69</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>57 %</td>
<td>100</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>0 s</td>
<td>1,235 s</td>
</tr>
<tr>
<td></td>
<td>250 s</td>
<td>80</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>120</td>
<td>0 s</td>
<td>1,759 s</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>297 ppm</td>
<td>48 ppm</td>
<td>0</td>
<td>230</td>
<td>71 ppm</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>64 %</td>
<td>100</td>
<td>77</td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>0 s</td>
<td>1,277 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>110</td>
<td>100</td>
<td>6</td>
<td>0</td>
<td>120</td>
<td>0 s</td>
<td>1,830 s</td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>395 ppm</td>
<td>65 ppm</td>
<td>0</td>
<td>138</td>
<td>95 ppm</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>72 %</td>
<td>100</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>76</td>
<td>0 s</td>
<td>1,319 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>130</td>
<td>130</td>
<td>3</td>
<td>0</td>
<td>265</td>
<td>0 s</td>
<td>1,924 s</td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>494 ppm</td>
<td>81 ppm</td>
<td>0</td>
<td>288</td>
<td>118 ppm</td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration $\geq 50$ ppm during the first 300s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration $\geq 50$ ppm during the first 300s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.20. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV12Qr15 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>4 s&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4 s</td>
<td>0 s</td>
<td>5 ppm</td>
<td>0 s</td>
<td>17 ppm</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>50 ppm&lt;sup&gt;c&lt;/sup&gt;</td>
<td>50 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
<tr>
<td>51</td>
<td>7 %</td>
<td>37 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>9 s</td>
<td>9 s</td>
<td>0 s</td>
<td>5 ppm</td>
<td>0 s</td>
<td>17 ppm</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
<tr>
<td>55</td>
<td>18 %</td>
<td>88 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>10 s</td>
<td>10 s</td>
<td>2 s</td>
<td>6 ppm</td>
<td>0 s</td>
<td>19 ppm</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
<tr>
<td>75</td>
<td>24 %</td>
<td>100 %</td>
<td>20 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>16 s</td>
<td>16 s</td>
<td>7 s</td>
<td>8 ppm</td>
<td>0 s</td>
<td>26 ppm</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
<tr>
<td>100</td>
<td>26 %</td>
<td>100 %</td>
<td>30 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>20 s</td>
<td>9 s</td>
<td>10 ppm</td>
<td>0 s</td>
<td>35 ppm</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
<tr>
<td>200</td>
<td>36 %</td>
<td>100 %</td>
<td>41 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>180 s</td>
<td>40 s</td>
<td>14 s</td>
<td>20 ppm</td>
<td>0 s</td>
<td>41 %</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
<tr>
<td>300</td>
<td>53 %</td>
<td>100 %</td>
<td>51 %</td>
<td>0 %</td>
<td>26 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>260 s</td>
<td>60 s</td>
<td>14 s</td>
<td>30 ppm</td>
<td>0 s</td>
<td>87 %</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
<tr>
<td>400</td>
<td>58 %</td>
<td>100 %</td>
<td>52 %</td>
<td>0 %</td>
<td>26 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>290 s</td>
<td>100 s</td>
<td>14 s</td>
<td>40 ppm</td>
<td>0 s</td>
<td>89 %</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
<tr>
<td>500</td>
<td>66 %</td>
<td>100 %</td>
<td>61 %</td>
<td>1 %</td>
<td>76 %</td>
<td>0 %</td>
<td>820 s</td>
<td>1,151 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>110 s</td>
<td>36 s</td>
<td>50 ppm</td>
<td>0 s</td>
<td>92 %</td>
<td>829 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>0 s</td>
<td>12 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>846 s</td>
<td>1,171 s</td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration ≥ 50 ppm during the first 300 s of pit and barn ventilation.  
b. Duration of time with H$_2$S concentration ≥ 50 ppm during the first 300 s of pit and barn ventilation.  
c. Maximum H$_2$S concentration during the first 300 s of pit and barn ventilation.  
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.  
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.  
Note: “-” indicates that the simulation ended before $T_{pel}$ was reached.
The following were observed for simulation case TV12 (Qr8, Qr15):

1. Quintiles I, II, III, and IV were always clear when $C_0 \leq 51$ ppm inside the manure pit for Qr15, and when $C_0 \leq 50$ ppm inside the manure pit for Qr15.
2. Quintile I was not contaminated when $C_0 \leq 100$ ppm for Qr8 and Qr15.
3. Quintile II was not contaminated when $C_0 \leq 200$ ppm for Qr8 and Qr15.
4. Quintile III was the only quintile that was always clear for all $C_0$ values ranging from 50 to 300 ppm with $C(H_2S) \leq 50$ ppm for Qr8 and Qr15. Quintile III was only 6% contaminated for Qr8 when $C_0 = 400$ ppm. Quintile III was only 1% contaminated for Qr15 when $C_0 = 500$ ppm. Quintile III had the lowest maximum concentration on the 0.15 m (6 in.) measurement plane of any quintile for all $C_0$ values ranging from 50 to 500 ppm.
5. Quintile V was never completely clear, even when $C_0 = 50$ ppm. This was because the concentration of H$_2$S gas on the 0.15 m (6 in.) plane after leaving the manure pit was always greatest at the at the outlet end of the barn for case TV12.
6. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 100$ ppm inside the manure pit and was 99% contaminated when $C_0 \geq 75$ ppm for Qr8.
7. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 75$ ppm inside the manure pit and was 88% contaminated when $C_0 \geq 55$ ppm for Qr15.

6.3.4.4 TV22

Simulation cases for pit-safety fan location (2,2) were performed using Q$_{ratio}$ of 30, 60, and 120. Figure 6.27 illustrates the air flow pattern through the barn and manure pit during ventilation for Qr30. Figure 6.28 shows the vertical H$_2$S gas distribution profiles at three section planes at time = 5s when the 50 ppm contour reached a maximum height above the barn floor for an initial manure pit H$_2$S concentration of 100 ppm.
Figure 6.27. Vertical cut plots through the tunnel ventilated barn showing velocity vectors and recirculation zones when time = 300s for simulation case TV22Qr30.
Figure 6.28. Vertical cut plots through the tunnel ventilated barn showing the H$_2$S gas concentration profile in the barn airspace 5s after the start of barn ventilation for simulation case TV22Qr30 for an initial manure pit H$_2$S concentration of 100 ppm.
Figure 6.29 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor resulting from barn and pit-safety ventilation with initial manure pit H$_2$S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (2,2) and $Q_{\text{ratios}}$ 30, 60, and 120. Table 6.21, Table 6.22, and Table 6.23 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (2,2) and $Q_{\text{ratios}}$ 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H$_2$S) \(\geq\) 50 ppm, duration of time when C(H$_2$S) \(\geq\) 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H$_2$S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.
Figure 6.29. Plot showing contaminated areas on the TV barn measurement plane during barn and pit-safety ventilation for case TV22.
Table 6.21. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV22Qr30 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>159 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>8 s&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8 s</td>
<td>0 s</td>
<td>29 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>162 s</td>
</tr>
<tr>
<td></td>
<td>50 ppm&lt;sup&gt;c&lt;/sup&gt;</td>
<td>50 ppm</td>
<td>42 ppm</td>
<td>17 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>173 s</td>
</tr>
<tr>
<td>51</td>
<td>7 %</td>
<td>36 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>162 s</td>
<td>423 s</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>30 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>173 s</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>43 ppm</td>
<td>17 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>210 s</td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>73 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>162 s</td>
<td>423 s</td>
</tr>
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<td>14 s</td>
<td>0 s</td>
<td>32 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>173 s</td>
</tr>
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<td>55 ppm</td>
<td>55 ppm</td>
<td>47 ppm</td>
<td>19 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>210 s</td>
</tr>
<tr>
<td>75</td>
<td>20 %</td>
<td>97 %</td>
<td>4 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>162 s</td>
<td>423 s</td>
</tr>
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<td>30 s</td>
<td>30 s</td>
<td>5 s</td>
<td>44 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
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</tr>
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<td>75 ppm</td>
<td>64 ppm</td>
<td>25 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
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</tr>
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<td>23 %</td>
<td>100 %</td>
<td>15 %</td>
<td>2 %</td>
<td>0 %</td>
<td>0 %</td>
<td>162 s</td>
<td>423 s</td>
</tr>
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<td></td>
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<td>40 s</td>
<td>6 s</td>
<td>34 ppm</td>
<td>0 s</td>
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<td>100 %</td>
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<td>25 %</td>
<td>28 %</td>
<td>44 %</td>
<td>162 s</td>
<td>423 s</td>
</tr>
<tr>
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<td>90 s</td>
<td>60 s</td>
<td>13 s</td>
<td>8 s</td>
<td>50 s</td>
<td>60 s</td>
<td>162 s</td>
<td>423 s</td>
</tr>
<tr>
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<td>200 ppm</td>
<td>200 ppm</td>
<td>170 ppm</td>
<td>68 ppm</td>
<td>63 ppm</td>
<td>162 s</td>
<td>423 s</td>
<td></td>
</tr>
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<td>72 %</td>
<td>100 %</td>
<td>51 %</td>
<td>54 %</td>
<td>68 %</td>
<td>87 %</td>
<td>162 s</td>
<td>423 s</td>
</tr>
<tr>
<td></td>
<td>120 s</td>
<td>60 s</td>
<td>30 s</td>
<td>53 s</td>
<td>75 s</td>
<td>100 s</td>
<td>162 s</td>
<td>423 s</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>255 ppm</td>
<td>176 ppm</td>
<td>101 ppm</td>
<td>94 ppm</td>
<td>162 s</td>
<td>423 s</td>
</tr>
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<td>100 %</td>
<td>76 %</td>
<td>78 %</td>
<td>85 %</td>
<td>88 %</td>
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<td>423 s</td>
</tr>
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<td></td>
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<td>70 s</td>
<td>30 s</td>
<td>86 s</td>
<td>121 s</td>
<td>136 s</td>
<td>162 s</td>
<td>423 s</td>
</tr>
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<td>135 ppm</td>
<td>125 ppm</td>
<td>162 s</td>
<td>423 s</td>
</tr>
<tr>
<td>500</td>
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<td>100 %</td>
<td>98 %</td>
<td>92 %</td>
<td>99 %</td>
<td>93 %</td>
<td>162 s</td>
<td>423 s</td>
</tr>
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<td>106 s</td>
<td>161 s</td>
<td>161 s</td>
<td>162 s</td>
<td>423 s</td>
</tr>
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<td>500 ppm</td>
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<td>293 ppm</td>
<td>169 ppm</td>
<td>157 ppm</td>
<td>162 s</td>
<td>423 s</td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: “-” indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.22. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV22Qr60 with $T_{pel}$ values.

<table>
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<th>$C_0$ (ppm)</th>
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<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %a</td>
<td>6 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>176 s4</td>
<td>471 s6</td>
</tr>
<tr>
<td></td>
<td>9 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>39 ppm</td>
<td>23 ppm</td>
<td>14 ppm</td>
<td>15 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>8 %</td>
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<td>0 %</td>
<td>179 s</td>
<td>474 s</td>
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<td></td>
</tr>
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<td>51 ppm</td>
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<td>14 ppm</td>
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<td></td>
</tr>
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<td>14 %</td>
<td>72 %</td>
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<td>0 %</td>
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<td>188 s</td>
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<td>0 s</td>
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</tr>
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<td>17 ppm</td>
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<td></td>
</tr>
<tr>
<td>75</td>
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<td>0 s</td>
<td>0 s</td>
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</tr>
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</tr>
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<td>0 s</td>
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<td></td>
</tr>
<tr>
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<td>100 ppm</td>
<td>78 ppm</td>
<td>47 ppm</td>
<td>28 ppm</td>
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</tr>
<tr>
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<td>10 %</td>
<td>7 %</td>
<td>35 %</td>
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</tr>
<tr>
<td></td>
<td>100 s</td>
<td>70 s</td>
<td>7 s</td>
<td>2 s</td>
<td>30 s</td>
<td>70 s</td>
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</tr>
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<td>93 ppm</td>
<td>56 ppm</td>
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</tr>
<tr>
<td>300</td>
<td>58 %</td>
<td>100 %</td>
<td>37 %</td>
<td>21 %</td>
<td>45 %</td>
<td>86 %</td>
<td>406 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150 s</td>
<td>90 s</td>
<td>9 s</td>
<td>3 s</td>
<td>95 s</td>
<td>130 s</td>
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</tr>
<tr>
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</tr>
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<td>35 %</td>
<td>75 %</td>
<td>88 %</td>
<td>442 s</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>100 s</td>
<td>9 s</td>
<td>35 s</td>
<td>140 s</td>
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</tr>
<tr>
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<td>100 %</td>
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<td>54 %</td>
<td>90 %</td>
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<td>110 s</td>
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<td>73 s</td>
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</tr>
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<td>500 ppm</td>
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<td>234 ppm</td>
<td>141 ppm</td>
<td>152 ppm</td>
<td></td>
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</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: “-” indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.23. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV22Qr120 with \( T_{pel} \) values.

<table>
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<th>( \text{Overall} )</th>
<th>( \text{V} )</th>
<th>( \text{IV} )</th>
<th>( \text{III} )</th>
<th>( \text{II} )</th>
<th>( \text{I} )</th>
<th>( T_{pel}(10) )</th>
<th>( T_{pel}(1) )</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1 ( % )(^a)</td>
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<td>0 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>205 ( s )(^d)</td>
<td>524 ( s )(^e)</td>
</tr>
<tr>
<td>8 s(^b)</td>
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<td>18 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 ppm(^c)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
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<td>8 ( % )</td>
<td>39 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
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<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51 ppm (^c)</td>
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<td></td>
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</tr>
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<td>0 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>210 ( s )</td>
<td>537 ( s )</td>
</tr>
<tr>
<td>16 s</td>
<td>16 s</td>
<td>42 ppm</td>
<td>20 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 ppm (^c)</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>75</td>
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<td>100 ( % )</td>
<td>1 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>255 ( s )</td>
<td>580 ( s )</td>
</tr>
<tr>
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<td>0 s</td>
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</tr>
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<td>75 ppm (^c)</td>
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</tr>
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<td>100 ( % )</td>
<td>11 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>0 ( % )</td>
<td>302 ( s )</td>
<td>622 ( s )</td>
</tr>
<tr>
<td>50 s</td>
<td>50 s</td>
<td>5 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 ppm (^c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>36 ( % )</td>
<td>100 ( % )</td>
<td>29 ( % )</td>
<td>4 ( % )</td>
<td>4 ( % )</td>
<td>42 ( % )</td>
<td>401 ( s )</td>
<td>-</td>
</tr>
<tr>
<td>110 s</td>
<td>110 s</td>
<td>2 ( % )</td>
<td>2 ( % )</td>
<td>40 ( s )</td>
<td>80 ( s )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 ppm (^c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>56 ( % )</td>
<td>100 ( % )</td>
<td>36 ( % )</td>
<td>11 ( % )</td>
<td>44 ( % )</td>
<td>87 ( % )</td>
<td>456 ( s )</td>
<td>-</td>
</tr>
<tr>
<td>140 s</td>
<td>140 s</td>
<td>8 ( % )</td>
<td>2 ( % )</td>
<td>110 ( s )</td>
<td>120 ( s )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 ppm (^c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>63 ( % )</td>
<td>100 ( % )</td>
<td>41 ( % )</td>
<td>16 ( % )</td>
<td>72 ( % )</td>
<td>88 ( % )</td>
<td>495 ( s )</td>
<td>-</td>
</tr>
<tr>
<td>200 s</td>
<td>200 s</td>
<td>3 ( % )</td>
<td>3 ( % )</td>
<td>135 ( s )</td>
<td>186 ( s )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400 ppm (^c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>71 ( % )</td>
<td>100 ( % )</td>
<td>47 ( % )</td>
<td>29 ( % )</td>
<td>86 ( % )</td>
<td>93 ( % )</td>
<td>524 ( s )</td>
<td>-</td>
</tr>
<tr>
<td>240 s</td>
<td>240 s</td>
<td>9 ( % )</td>
<td>6 ( % )</td>
<td>210 ( s )</td>
<td>220 ( s )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 ppm (^c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( a. \) Percent of area with \( \text{H}_2\text{S} \) concentration \( \geq 50 \text{ ppm} \) during the first 300s of pit and barn ventilation.

\( b. \) Duration of time with \( \text{H}_2\text{S} \) concentration \( \geq 50 \text{ ppm} \) during the first 300s of pit and barn ventilation.

\( c. \) Maximum \( \text{H}_2\text{S} \) concentration during the first 300s of pit and barn ventilation.

\( d. \) Manure pit-safety ventilation duration required to reach a maximum pit \( \text{H}_2\text{S} \) concentration of 10 ppm.

\( e. \) Manure pit-safety ventilation duration required to reach a maximum pit \( \text{H}_2\text{S} \) concentration of 1 ppm.

Note: "-" indicates that the simulation ended before \( T_{pel} \) was reached.
The following were observed for simulation case TV22:

1. Quintiles I, II, III, and IV were always clear when $C_0 \leq 55$ ppm inside the manure pit.
2. Quintile I had the lowest maximum concentration on the 0.15 m (6 in.) measurement plane of any quintile for all $C_0$ values ranging from 50 to 500 ppm.
3. Quintiles I and II were not contaminated when $C_0 \leq 100$ ppm for all three $Q_{ratio}$.
4. Quintile III was not contaminated when $C_0 \leq 75$ ppm for $Q_{ratio} 30$ and when $C_0 \leq 100$ ppm for $Q_{ratio} 60$ and $Q_{ratio} 120$. Quintile III was only 2% contaminated when $C_0 = 100$ ppm for $Q_{ratio} 30$, and was 25%, 10%, and 4% contaminated when $C_0 = 200$ ppm for $Q_{ratio} 30$, $Q_{ratio} 60$, and $Q_{ratio} 120$, respectively.
5. Quintile IV was only 4%, 2%, and 1% contaminated when $C_0 = 75$ ppm for $Q_{ratio} 30$, $Q_{ratio} 60$, and $Q_{ratio} 120$, respectively.
6. Quintile V was never completely clear, even when $C_0 = 50$ ppm. This was because the concentration of H$_2$S gas on the 0.15 m (6 in.) plane after leaving the manure pit was always greatest at the outlet end of the barn for case TV22.
7. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 75$ ppm inside the manure pit for $Q_{ratio} 60$ and $Q_{ratio} 120$, and 97% contaminated for $Q_{ratio} 30$. Quintile V was 100% contaminated when $C_0 \geq 100$ ppm for $Q_{ratio} 30$. Quintile V was 73%, 72%, and 72% contaminated when $C_0 = 55$ ppm for $Q_{ratio} 30$, $Q_{ratio} 60$, and $Q_{ratio} 120$, respectively.

**6.3.4.5 TV31**

Simulation cases for pit-safety fan location (3,1) were performed using $Q_{ratio}$ of 30, 60, and 120. Figure 6.30 illustrates the air flow pattern through the barn and manure pit during ventilation for $Q_{ratio} 30$. Figure 6.31 shows the vertical H$_2$S gas distribution profiles at three section planes at time = 5s when the 50 ppm contour reached a maximum height above the barn floor for an initial manure pit H$_2$S concentration of 100 ppm.
Figure 6.30. Vertical cut plots through the tunnel ventilated barn showing velocity vectors and recirculation zones when time = 300s for simulation case TV31Qr30.
Figure 6.31. Vertical cut plots through the tunnel ventilated barn showing the H$_2$S gas concentration profile in the barn airspace 5s after the start of barn ventilation for simulation case TV31Qr30 for an initial manure pit H$_2$S concentration of 100 ppm.
Figure 6.32 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor resulting from barn and pit-safety ventilation with initial manure pit H₂S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (3,1) and Q_{ ratios } 30, 60, and 120. Table 6.24, Table 6.25, and Table 6.26 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (3,1) and Q_{ ratios } 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H₂S) \geq 50 \text{ ppm}, duration of time when C(H₂S) \geq 50 \text{ ppm}, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H₂S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.
Figure 6.32. Plot showing contaminated areas on the TV barn measurement plane during barn and pit-safety ventilation for case TV31.
Table 6.24. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV31Qr30 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>206 s&lt;sup&gt;d&lt;/sup&gt;</td>
<td>19 ppm</td>
</tr>
<tr>
<td></td>
<td>8 %&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8 s</td>
<td>0 s</td>
<td>8 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>310 s&lt;sup&gt;e&lt;/sup&gt;</td>
<td>19 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm&lt;sup&gt;c&lt;/sup&gt;</td>
<td>50 ppm</td>
<td>37 ppm</td>
<td>19 ppm</td>
<td>20 ppm</td>
<td>19 ppm</td>
<td>207 s</td>
<td>19 ppm</td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>42 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>207 s</td>
<td>19 ppm</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>311 s</td>
<td>19 ppm</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>38 ppm</td>
<td>20 ppm</td>
<td>19 ppm</td>
<td>212 s</td>
<td>21 ppm</td>
<td>19 ppm</td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>74 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>212 s</td>
<td>21 ppm</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>20 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>314 s</td>
<td>21 ppm</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>41 ppm</td>
<td>9 ppm</td>
<td>22 ppm</td>
<td>28 ppm</td>
<td>229 s</td>
<td>28 ppm</td>
</tr>
<tr>
<td>75</td>
<td>20 %</td>
<td>100 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>229 s</td>
<td>28 ppm</td>
</tr>
<tr>
<td></td>
<td>40 s</td>
<td>40 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>329 s</td>
<td>28 ppm</td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>55 ppm</td>
<td>12 ppm</td>
<td>30 ppm</td>
<td>28 ppm</td>
<td>229 s</td>
<td>28 ppm</td>
</tr>
<tr>
<td>100</td>
<td>22 %</td>
<td>100 %</td>
<td>11 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>242 s</td>
<td>38 ppm</td>
</tr>
<tr>
<td></td>
<td>60 s</td>
<td>60 s</td>
<td>5 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>345 s</td>
<td>38 ppm</td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>74 ppm</td>
<td>17 ppm</td>
<td>39 ppm</td>
<td>38 ppm</td>
<td>242 s</td>
<td>38 ppm</td>
</tr>
<tr>
<td>200</td>
<td>32 %</td>
<td>100 %</td>
<td>31 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>268 s</td>
<td>38 ppm</td>
</tr>
<tr>
<td></td>
<td>100 s</td>
<td>100 s</td>
<td>7 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>32 s</td>
<td>38 ppm</td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>148 ppm</td>
<td>33 ppm</td>
<td>79 ppm</td>
<td>75 ppm</td>
<td>268 s</td>
<td>75 ppm</td>
</tr>
<tr>
<td>300</td>
<td>43 %</td>
<td>100 %</td>
<td>41 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>286 s</td>
<td>75 ppm</td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>160 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>286 s</td>
<td>75 ppm</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>221 ppm</td>
<td>50 ppm</td>
<td>118 ppm</td>
<td>113 ppm</td>
<td>286 s</td>
<td>113 ppm</td>
</tr>
<tr>
<td>400</td>
<td>47 %</td>
<td>100 %</td>
<td>42 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>299 s</td>
<td>75 ppm</td>
</tr>
<tr>
<td></td>
<td>170 s</td>
<td>170 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>299 s</td>
<td>75 ppm</td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>295 ppm</td>
<td>40 s</td>
<td>72 s</td>
<td>86 s</td>
<td>299 s</td>
<td>86 s</td>
</tr>
<tr>
<td>500</td>
<td>54 %</td>
<td>100 %</td>
<td>44 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>310 s</td>
<td>86 s</td>
</tr>
<tr>
<td></td>
<td>180 s</td>
<td>180 s</td>
<td>10 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>310 s</td>
<td>86 s</td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>369 ppm</td>
<td>83 ppm</td>
<td>197 ppm</td>
<td>188 ppm</td>
<td>310 s</td>
<td>188 ppm</td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration $\geq$ 50 ppm during the first 300 s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration $\geq$ 50 ppm during the first 300 s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300 s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.25. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV31Qr60 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V (For first 300s)</th>
<th>IV (For first 300s)</th>
<th>III (For first 300s)</th>
<th>II (For first 300s)</th>
<th>I (For first 300s)</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %$^a$</td>
<td>5%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>8 s$^b$</td>
<td>8 ppm</td>
<td>50 ppm</td>
<td>0 ppm</td>
<td>0 ppm</td>
<td>0 ppm</td>
<td>0 ppm</td>
<td>0 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 ppm</td>
<td>36 ppm</td>
<td>6 ppm</td>
<td>16 ppm</td>
<td>16 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>41%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>37 ppm</td>
<td>6 ppm</td>
<td>16 ppm</td>
<td>16 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>74 %</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>16 %</td>
<td>16%</td>
<td>0%</td>
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</tr>
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<td>55 ppm</td>
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</tr>
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<td>1%</td>
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<td>0%</td>
<td>0%</td>
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<td>0%</td>
</tr>
<tr>
<td></td>
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<td>40 s</td>
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<td>0%</td>
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<td>11%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>50 s</td>
<td>50 s</td>
<td>4 s</td>
<td>0%</td>
<td>0%</td>
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<td>31 ppm</td>
<td>32 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>29 %</td>
<td>100%</td>
<td>30%</td>
<td>0%</td>
<td>4%</td>
<td>0%</td>
<td>12%</td>
<td>38 s</td>
</tr>
<tr>
<td></td>
<td>110 s</td>
<td>110 s</td>
<td>7 s</td>
<td>0%</td>
<td>40 s</td>
<td>64 ppm</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>145 ppm</td>
<td>23 ppm</td>
<td>63 ppm</td>
<td>64 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>40 %</td>
<td>100%</td>
<td>41%</td>
<td>0%</td>
<td>22%</td>
<td>37%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>160 s</td>
<td>9 s</td>
<td>0%</td>
<td>80 s</td>
<td>77 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>217 ppm</td>
<td>34 ppm</td>
<td>94 ppm</td>
<td>96 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>46 %</td>
<td>100%</td>
<td>42%</td>
<td>0%</td>
<td>39%</td>
<td>52%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>46 %</td>
<td>100%</td>
<td>42%</td>
<td>0%</td>
<td>39%</td>
<td>52%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>180 s</td>
<td>180 s</td>
<td>9 s</td>
<td>0%</td>
<td>112 s</td>
<td>118 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>289 ppm</td>
<td>46 ppm</td>
<td>126 ppm</td>
<td>128 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>52 %</td>
<td>100%</td>
<td>44%</td>
<td>2%</td>
<td>46%</td>
<td>70%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 s</td>
<td>200 s</td>
<td>9 s</td>
<td>40 s</td>
<td>122 s</td>
<td>128 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>362 ppm</td>
<td>57 ppm</td>
<td>157 ppm</td>
<td>160 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.26. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV31Qr120 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>284 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>8 %&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8 s</td>
<td>50 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>15 ppm</td>
<td>17 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ppm&lt;sup&gt;c&lt;/sup&gt;</td>
<td>36 ppm</td>
<td>5 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>41 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>288 s</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>37 ppm</td>
<td>5 ppm</td>
<td>15 ppm</td>
<td>17 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>74 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>301 s</td>
</tr>
<tr>
<td></td>
<td>16 s</td>
<td>16 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>39 ppm</td>
<td>6 ppm</td>
<td>16 ppm</td>
<td>19 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>20 %</td>
<td>100 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>339 s</td>
</tr>
<tr>
<td></td>
<td>40 s</td>
<td>40 s</td>
<td>2 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>54 ppm</td>
<td>8 ppm</td>
<td>22 ppm</td>
<td>25 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>22 %</td>
<td>100 %</td>
<td>11 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>367 s</td>
</tr>
<tr>
<td></td>
<td>50 s</td>
<td>50 s</td>
<td>4 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>72 ppm</td>
<td>11 ppm</td>
<td>29 ppm</td>
<td>34 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>29 %</td>
<td>100 %</td>
<td>30 %</td>
<td>0 %</td>
<td>2 %</td>
<td>0 %</td>
<td>15 %</td>
<td>466 s</td>
</tr>
<tr>
<td></td>
<td>70 s</td>
<td>70 s</td>
<td>7 s</td>
<td>0 s</td>
<td>30 s</td>
<td>0 s</td>
<td>49 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>143 ppm</td>
<td>21 ppm</td>
<td>59 ppm</td>
<td>67 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>41 %</td>
<td>100 %</td>
<td>38 %</td>
<td>0 %</td>
<td>17 %</td>
<td>0 %</td>
<td>51 %</td>
<td>519 s</td>
</tr>
<tr>
<td></td>
<td>140 s</td>
<td>110 s</td>
<td>8 s</td>
<td>0 s</td>
<td>90 s</td>
<td>0 s</td>
<td>136 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>215 ppm</td>
<td>32 ppm</td>
<td>88 ppm</td>
<td>101 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>50 %</td>
<td>100 %</td>
<td>42 %</td>
<td>0 %</td>
<td>35 %</td>
<td>0 %</td>
<td>72 %</td>
<td>553 s</td>
</tr>
<tr>
<td></td>
<td>180 s</td>
<td>140 s</td>
<td>9 s</td>
<td>0 s</td>
<td>145 s</td>
<td>0 s</td>
<td>167 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>287 ppm</td>
<td>42 ppm</td>
<td>118 ppm</td>
<td>135 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>55 %</td>
<td>100 %</td>
<td>43 %</td>
<td>1 %</td>
<td>50 %</td>
<td>0 %</td>
<td>83 %</td>
<td>572 s</td>
</tr>
<tr>
<td></td>
<td>230 s</td>
<td>180 s</td>
<td>9 s</td>
<td>20 s</td>
<td>182 s</td>
<td>0 s</td>
<td>227 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>358 ppm</td>
<td>53 ppm</td>
<td>147 ppm</td>
<td>168 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.
Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
The following were observed for simulation case TV31:

1. Quintiles I, II, III, and IV were always clear when $C_0 \leq 55$ ppm inside the manure pit.
2. Quintiles I and II were not contaminated when $C_0 \leq 100$ ppm for all three $Q_{\text{ratio}}$.
3. Quintile III had the lowest maximum concentration on the 0.15 m (6 in.) measurement plane of any quintile for all $C_0$ values ranging from 50 to 500 ppm.
4. Quintile III was only 8% contaminated when $C_0 = 400$ ppm for Qr30, and was 28%, 2%, and 1% contaminated when $C_0 = 500$ ppm for Qr30, Qr60, and Qr120, respectively.
5. Quintile III was not contaminated when $C_0 \leq 300$ ppm for all three $Q_{\text{ratio}}$.
6. Quintile IV was only 1% contaminated when $C_0 = 75$ ppm for all three $Q_{\text{ratio}}$.
7. Quintile V was never completely clear, even when $C_0 = 50$ ppm. This was because the concentration of $H_2S$ gas on the 0.15 m (6 in.) plane after leaving the manure pit was always greatest at the at the outlet end of the barn for case TV31.
8. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 75$ ppm inside the manure pit for all three $Q_{\text{ratio}}$. Quintile V was 74% contaminated when $C_0 = 55$ ppm for all three $Q_{\text{ratio}}$.

**6.3.4.6 TV32**

Simulation cases for pit-safety fan location (3,2) were performed using $Q_{\text{ratio}}$ of 8, 15, 30, 60, and 120. Figure 6.33 illustrates the air flow pattern through the barn and manure pit during ventilation for Qr30. Figure 6.34 shows the vertical $H_2S$ gas distribution profiles at three section planes at time = 5s when the 50 ppm contour reached a maximum height above the barn floor for an initial manure pit $H_2S$ concentration of 100 ppm.
Figure 6.33. Vertical cut plots through the tunnel ventilated barn showing velocity vectors and recirculation zones when time = 300s for simulation case TV32Qr30.
Figure 6.34. Vertical cut plots through the tunnel ventilated barn showing the H$_2$S gas concentration profile in the barn airspace 5s after the start of barn ventilation for simulation case TV32Qr30 for an initial manure pit H$_2$S concentration of 100 ppm.
Figure 6.35 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor resulting from barn and pit-safety ventilation with initial manure pit H₂S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (3,2) and Q_{ratios} 30, 60, and 120. Figure 6.36 shows two additional simulation cases for Q_{ratios} 8 and 15. Table 6.27, Table 6.28, and Table 6.29 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (3,2) and Q_{ratios} 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H₂S) ≥ 50 ppm, duration of time when C(H₂S) ≥ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H₂S concentration of 10 or 1 ppm anywhere inside the manure pit airspace. Table 6.30 and Table 6.31 the comparison statistics for additional Q_{ratios} 8 and 15, respectively.
Figure 6.35. Plot showing contaminated areas on the TV barn measurement plane during barn and pit-safety ventilation for case TV32.
Table 6.27. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV32Qr30 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}$(10)</th>
<th>$T_{pel}$(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %$^a$</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>164 s$d$</td>
<td>257 s$^e$</td>
</tr>
<tr>
<td></td>
<td>8 s$^b$</td>
<td>8 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>50 ppm</td>
<td>36 ppm</td>
<td>11 ppm</td>
<td>16 ppm</td>
<td>13 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>42 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>165 s</td>
<td>258 s</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 ppm$^c$</td>
<td>51 ppm</td>
<td>37 ppm</td>
<td>11 ppm</td>
<td>16 ppm</td>
<td>13 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>15 %</td>
<td>74 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>168 s</td>
<td>262 s</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>20 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 ppm$^c$</td>
<td>55 ppm</td>
<td>40 ppm</td>
<td>12 ppm</td>
<td>17 ppm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>20 %</td>
<td>100 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>176 s</td>
<td>279 s</td>
</tr>
<tr>
<td></td>
<td>40 s</td>
<td>40 s</td>
<td>3 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm$^c$</td>
<td>75 ppm</td>
<td>55 ppm</td>
<td>16 ppm</td>
<td>24 ppm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>22 %</td>
<td>100 %</td>
<td>11 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>187 s</td>
<td>294 s</td>
</tr>
<tr>
<td></td>
<td>50 s</td>
<td>50 s</td>
<td>5 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm$^c$</td>
<td>100 ppm</td>
<td>73 ppm</td>
<td>22 ppm</td>
<td>32 ppm</td>
<td>25 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>29 %</td>
<td>100 %</td>
<td>30 %</td>
<td>0 %</td>
<td>16 %</td>
<td>1 %</td>
<td>219 s</td>
<td>325 s</td>
</tr>
<tr>
<td></td>
<td>90 s</td>
<td>90 s</td>
<td>7 s</td>
<td>0 s</td>
<td>24 s</td>
<td>1 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm$^c$</td>
<td>200 ppm</td>
<td>146 ppm</td>
<td>44 ppm</td>
<td>63 ppm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>39 %</td>
<td>100 %</td>
<td>41 %</td>
<td>6 %</td>
<td>29 %</td>
<td>21 %</td>
<td>236 s</td>
<td>342 s</td>
</tr>
<tr>
<td></td>
<td>110 s</td>
<td>110 s</td>
<td>9 s</td>
<td>20 s</td>
<td>36 s</td>
<td>19 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm$^c$</td>
<td>300 ppm</td>
<td>219 ppm</td>
<td>65 ppm</td>
<td>95 ppm</td>
<td>76 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>42 %</td>
<td>100 %</td>
<td>42 %</td>
<td>12 %</td>
<td>30 %</td>
<td>25 %</td>
<td>248 s</td>
<td>354 s</td>
</tr>
<tr>
<td></td>
<td>120 s</td>
<td>120 s</td>
<td>9 s</td>
<td>35 s</td>
<td>48 s</td>
<td>25 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm$^c$</td>
<td>400 ppm</td>
<td>292 ppm</td>
<td>87 ppm</td>
<td>127 ppm</td>
<td>101 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>46 %</td>
<td>100 %</td>
<td>44 %</td>
<td>21 %</td>
<td>34 %</td>
<td>30 %</td>
<td>257 s</td>
<td>363 s</td>
</tr>
<tr>
<td></td>
<td>130 s</td>
<td>130 s</td>
<td>10 s</td>
<td>45 s</td>
<td>58 s</td>
<td>26 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm$^c$</td>
<td>500 ppm</td>
<td>364 ppm</td>
<td>109 ppm</td>
<td>158 ppm</td>
<td>127 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

a. Percent of area with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.28. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV32Qr60 with T_{pel} values.

<table>
<thead>
<tr>
<th>C_{0} (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>T_{pel(10)}</th>
<th>T_{pel(1)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %^{a}</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>224 s^{d}</td>
<td>484 s^{e}</td>
</tr>
<tr>
<td></td>
<td>8 %</td>
<td>8 s</td>
<td>0 s</td>
<td>6 ppm</td>
<td>0 s</td>
<td>0 ppm</td>
<td>226 s</td>
<td>488 s</td>
</tr>
<tr>
<td></td>
<td>8 s</td>
<td>50 ppm</td>
<td>36 ppm</td>
<td>0 s</td>
<td>18 ppm</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>15 %</td>
<td>74 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>232 s</td>
<td>498 s</td>
</tr>
<tr>
<td></td>
<td>16 %</td>
<td>16 s</td>
<td>0 s</td>
<td>6 ppm</td>
<td>0 s</td>
<td>0 ppm</td>
<td>253 s</td>
<td>530 s</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>40 ppm</td>
<td>0 s</td>
<td>19 ppm</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>20 %</td>
<td>100 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>290 s</td>
<td>557 s</td>
</tr>
<tr>
<td></td>
<td>40 %</td>
<td>40 s</td>
<td>2 s</td>
<td>8 ppm</td>
<td>0 s</td>
<td>0 ppm</td>
<td>364 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>54 ppm</td>
<td>2 s</td>
<td>26 ppm</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>22 %</td>
<td>100 %</td>
<td>11 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 s</td>
<td>50 s</td>
<td>4 s</td>
<td>11 ppm</td>
<td>0 s</td>
<td>0 ppm</td>
<td>31 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>72 ppm</td>
<td>0 s</td>
<td>35 ppm</td>
<td>0 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>29 %</td>
<td>100 %</td>
<td>31 %</td>
<td>0 %</td>
<td>10 %</td>
<td>4 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>110 s</td>
<td>110 s</td>
<td>7 s</td>
<td>0 s</td>
<td>20 s</td>
<td>7 s</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>200 ppm</td>
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<td>23 ppm</td>
<td>71 ppm</td>
<td>60 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>36 %</td>
<td>100 %</td>
<td>41 %</td>
<td>0 %</td>
<td>18 %</td>
<td>22 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>160 s</td>
<td>9 s</td>
<td>0 s</td>
<td>42 s</td>
<td>31 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
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<td>34 ppm</td>
<td>106 ppm</td>
<td>90 ppm</td>
<td></td>
<td></td>
</tr>
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<td>40 %</td>
<td>100 %</td>
<td>42 %</td>
<td>0 %</td>
<td>28 %</td>
<td>29 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>170 s</td>
<td>170 s</td>
<td>9 s</td>
<td>0 s</td>
<td>74 s</td>
<td>52 s</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>400 ppm</td>
<td>288 ppm</td>
<td>45 ppm</td>
<td>141 ppm</td>
<td>120 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>43 %</td>
<td>100 %</td>
<td>44 %</td>
<td>1 %</td>
<td>33 %</td>
<td>38 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>180 s</td>
<td>180 s</td>
<td>9 s</td>
<td>40 s</td>
<td>106 s</td>
<td>74 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>360 ppm</td>
<td>57 ppm</td>
<td>177 ppm</td>
<td>150 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H_{2}S concentration ≥ 50 ppm during the first 300 s of pit and barn ventilation.
b. Duration of time with H_{2}S concentration ≥ 50 ppm during the first 300 s of pit and barn ventilation.
c. Maximum H_{2}S concentration during the first 300 s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H_{2}S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H_{2}S concentration of 1 ppm.

Note: "}" indicates that the simulation ended before T_{pel} was reached.
Table 6.29. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV32Qr120 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %</td>
<td>5%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>311 s</td>
<td>573 s</td>
</tr>
<tr>
<td>8%</td>
<td>8 s</td>
<td>50 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>50 ppm</td>
<td></td>
</tr>
<tr>
<td>50 ppm</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>8%</td>
<td>41%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>314 s</td>
<td>576 s</td>
</tr>
<tr>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>51 ppm</td>
<td></td>
</tr>
<tr>
<td>51 ppm</td>
<td></td>
<td>51 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>15%</td>
<td>74%</td>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>322 s</td>
<td>588 s</td>
</tr>
<tr>
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<td>0 s</td>
<td>55 ppm</td>
<td></td>
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<tr>
<td>55 ppm</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>20%</td>
<td>100%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>345 s</td>
<td>639 s</td>
</tr>
<tr>
<td>30 s</td>
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<td>2 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>75 ppm</td>
<td></td>
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<tr>
<td>75 ppm</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>22%</td>
<td>100%</td>
<td>11%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>377 s</td>
<td>688 s</td>
</tr>
<tr>
<td>50 s</td>
<td>50 s</td>
<td>4 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>100 ppm</td>
<td></td>
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<tr>
<td>100 ppm</td>
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<td></td>
</tr>
<tr>
<td>200</td>
<td>28%</td>
<td>100%</td>
<td>30%</td>
<td>0%</td>
<td>0%</td>
<td>2%</td>
<td>441 s</td>
<td></td>
</tr>
<tr>
<td>70 s</td>
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<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>200 ppm</td>
<td></td>
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<tr>
<td>200 ppm</td>
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<td>200 ppm</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>38%</td>
<td>100%</td>
<td>38%</td>
<td>0%</td>
<td>0%</td>
<td>13%</td>
<td>486 s</td>
<td></td>
</tr>
<tr>
<td>120 s</td>
<td>90 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>100 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 ppm</td>
<td></td>
<td>300 ppm</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>47%</td>
<td>100%</td>
<td>42%</td>
<td>0%</td>
<td>0%</td>
<td>23%</td>
<td>534 s</td>
<td></td>
</tr>
<tr>
<td>170 s</td>
<td>110 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>152 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400 ppm</td>
<td></td>
<td>400 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>52%</td>
<td>100%</td>
<td>43%</td>
<td>0%</td>
<td>0%</td>
<td>35%</td>
<td>573 s</td>
<td></td>
</tr>
<tr>
<td>220 s</td>
<td>150 s</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>202 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 ppm</td>
<td></td>
<td>500 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
The following were observed for simulation case TV32 (Qr30, Qr60, Qr120):

1. Quintile V was never completely clear, even when $C_0 = 50$ ppm. This was because the concentration of $H_2S$ gas on the 0.15 m (6 in.) plane after leaving the manure pit was always greatest at the outlet end of the barn.

2. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 75$ ppm inside the manure pit for all three $Q_{r\text{atios}}$. Quintile V was 74% contaminated when $C_0 = 55$ ppm for all three $Q_{r\text{atios}}$.

3. Quintiles I, II, III, and IV were always clear when $C_0 \leq 55$ ppm inside the manure pit. Quintile IV was only 1% contaminated when $C_0 = 75$ ppm for all three $Q_{r\text{atios}}$.

4. Quintile III was always clear for Qr120. Quintile III was not contaminated when $C_0 \leq 200$ ppm, and was only 6% contaminated when $C_0 = 300$ ppm for Qr30. Quintile III was not contaminated when $C_0 \leq 400$ ppm, and was only 1% contaminated when $C_0 = 500$ ppm for Qr60.

5. Quintile III had the lowest maximum concentration on the 0.15 m (6 in.) measurement plane of any quintile for all $C_0$ values ranging from 50 to 500 ppm.

6. Quintiles I and II were not contaminated when $C_0 \leq 100$ ppm for all three $Q_{r\text{atios}}$. 

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Figure 6.36. Plot showing contaminated areas on the TV barn measurement plane during barn and pit-safety ventilation for additional fan cases TV32 Qr8 and Qr15.
Table 6.30. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV32Qr8 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel(10)}$</th>
<th>$T_{pel(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ppm</td>
<td>2 % $^a$</td>
<td>9 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 s</td>
<td>72 s $^d$</td>
</tr>
<tr>
<td></td>
<td>9 s $^b$</td>
<td>9 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>41 ppm</td>
<td>10 ppm</td>
<td>13 ppm</td>
<td>25 ppm</td>
<td>50 ppm</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td>75 ppm</td>
<td>11 %</td>
<td>56 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>14 s</td>
<td>14 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>41 ppm</td>
<td>10 ppm</td>
<td>13 ppm</td>
<td>25 ppm</td>
<td>50 ppm</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td>100 ppm</td>
<td>17 %</td>
<td>83 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>20 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>45 ppm</td>
<td>10 ppm</td>
<td>14 ppm</td>
<td>28 ppm</td>
<td>50 ppm</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td>200 ppm</td>
<td>22 %</td>
<td>100 %</td>
<td>10 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>40 s</td>
<td>40 s</td>
<td>4 s</td>
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<td>0 s</td>
<td>0 s</td>
<td>0 %</td>
<td>72 s $^a$</td>
</tr>
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<td>75 ppm</td>
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<td>19 ppm</td>
<td>38 ppm</td>
<td>50 ppm</td>
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<td>24 %</td>
<td>100 %</td>
<td>20 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1 %</td>
<td>72 s $^a$</td>
</tr>
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<td>7 s</td>
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<td>0 s</td>
<td>1 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
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<td>100 ppm</td>
<td>81 ppm</td>
<td>19 ppm</td>
<td>26 ppm</td>
<td>50 ppm</td>
<td>72 s $^a$</td>
<td></td>
</tr>
<tr>
<td>400 ppm</td>
<td>31 %</td>
<td>100 %</td>
<td>39 %</td>
<td>0 %</td>
<td>2 %</td>
<td>0 %</td>
<td>14 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>50 s</td>
<td>50 s</td>
<td>11 s</td>
<td>0 s</td>
<td>3 %</td>
<td>0 s</td>
<td>4 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>200 ppm</td>
<td>162 ppm</td>
<td>38 ppm</td>
<td>52 ppm</td>
<td>101 ppm</td>
<td>72 s $^a$</td>
<td></td>
</tr>
<tr>
<td>500 ppm</td>
<td>22 %</td>
<td>100 %</td>
<td>20 %</td>
<td>0 %</td>
<td>2 %</td>
<td>0 %</td>
<td>14 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>50 s</td>
<td>50 s</td>
<td>17 s</td>
<td>0 s</td>
<td>3 %</td>
<td>0 s</td>
<td>4 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>244 ppm</td>
<td>57 ppm</td>
<td>78 ppm</td>
<td>151 ppm</td>
<td>72 s $^a$</td>
<td></td>
</tr>
<tr>
<td>750 ppm</td>
<td>39 %</td>
<td>100 %</td>
<td>41 %</td>
<td>11 %</td>
<td>20 %</td>
<td>0 %</td>
<td>22 %</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>50 s</td>
<td>50 s</td>
<td>17 s</td>
<td>9 s</td>
<td>11 s</td>
<td>0 s</td>
<td>6 s</td>
<td>72 s $^a$</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>300 ppm</td>
<td>244 ppm</td>
<td>57 ppm</td>
<td>78 ppm</td>
<td>151 ppm</td>
<td>72 s $^a$</td>
<td></td>
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<tr>
<td>Note:</td>
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<tr>
<td>a.</td>
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<tr>
<td>b.</td>
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<td></td>
</tr>
<tr>
<td>c.</td>
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</tr>
<tr>
<td>d.</td>
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<td></td>
</tr>
<tr>
<td>e.</td>
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</tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

*a. Percent of area with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
*b. Duration of time with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
*c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
*d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
*e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.
Note: “-“ indicates that the simulation ended before $T_{pel}$ was reached.
Table 6.31. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case TV32Qr15 with T_{pel} values.

<table>
<thead>
<tr>
<th>C_0 (ppm)</th>
<th>Overall</th>
<th>Barn Quintile (For first 300s)</th>
<th></th>
<th>T_{pel}(10)</th>
<th>T_{pel}(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 %\textsuperscript{a}</td>
<td>6 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td></td>
<td>8 s\textsuperscript{b}</td>
<td>8 s</td>
<td>0 s</td>
<td>0 s</td>
<td>14 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm\textsuperscript{c}</td>
<td>50 ppm</td>
<td>37 ppm</td>
<td>37 ppm</td>
<td>14 ppm</td>
</tr>
<tr>
<td>51</td>
<td>9 %</td>
<td>47 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td></td>
<td>12 s</td>
<td>12 s</td>
<td>0 s</td>
<td>0 s</td>
<td>14 ppm</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>38 ppm</td>
<td>38 ppm</td>
<td>14 ppm</td>
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<tr>
<td>55</td>
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<td>75 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
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<td></td>
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<td>0 s</td>
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<td>1 %</td>
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<td>100 %</td>
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<tr>
<td>300</td>
<td>42 %</td>
<td>100 %</td>
<td>43 %</td>
<td>22 %</td>
<td>30 %</td>
</tr>
<tr>
<td></td>
<td>90 s</td>
<td>90 s</td>
<td>30 s</td>
<td>30 s</td>
<td>20 s</td>
</tr>
<tr>
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<td>300 ppm</td>
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<td>30 %</td>
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<tr>
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<td>30 s</td>
<td>30 s</td>
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<td>39 %</td>
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<td>90 s</td>
<td>90 s</td>
<td>45 s</td>
<td>32 s</td>
<td>20 s</td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>374 ppm</td>
<td>374 ppm</td>
<td>139 ppm</td>
</tr>
</tbody>
</table>

a. Percent of area with H_{2}S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H_{2}S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H_{2}S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H_{2}S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H_{2}S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before T_{pel} was reached.
The following were observed for simulation case TV32 (Qr8, Qr15):

1. Quintiles I, II, III, and IV were always clear when $C_0 \leq 55$ ppm inside the manure pit.
2. Quintile I was not contaminated when $C_0 = 100$ ppm for Qr15, and only 1% contaminated for Qr8.
3. Quintile II was not contaminated when $C_0 \leq 100$ ppm for Qr8 and Qr15.
4. Quintile III had the lowest maximum concentration on the 0.15 m (6 in.) measurement plane of any quintile for all $C_0$ values ranging from 50 to 500 ppm for Qr8, but Quintile II had the lowest maximum concentration for Qr15.
5. Quintile III was only 11% and 22% contaminated when $C_0 = 300$ ppm for Qr8 and Qr15, respectively.
6. Quintile III was not contaminated when $C_0 \leq 200$ ppm for Qr8. Quintile III was only 6% contaminated when $C_0 = 200$ ppm for Qr15.
7. Quintile IV was only 10% and 1% contaminated when $C_0 = 75$ ppm for Qr8 and Qr15, respectively.
8. Quintile V was never completely clear, even when $C_0 = 50$ ppm. This was because the concentration of H$_2$S gas on the 0.15 m (6 in.) plane after leaving the manure pit was always greatest at the outlet end of the barn for case TV32.
9. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 75$ ppm inside the manure pit for Qr8 and Qr15.
10. Quintile V was 83% and 75% contaminated when $C_0 = 55$ ppm for Qr8 and Qr15, respectively.
6.4 Discussion of results

This section presents a discussion of the effects of different pit-safety ventilation fan locations and Q_{ratios} for tunnel ventilated barns on the contaminated area and duration of time when C(H_2S) ≥ 50 ppm in the barn airspace, the maximum H_2S concentration in the barn and within each quintile, and the duration of time required to reach T_{pel} during pit and barn ventilation. This discussion is for a specific barn size, ventilation configuration, and simulated initial and boundary conditions. Other barn sizes and ventilation configurations may result in clear zones large enough to safely relocate animals temporarily during pit and barn ventilation events. Analysis of contaminated areas within the barn airspace focused on a plane located 0.15 m (6 in.) above the barn floor and did not consider the recirculation of contaminant gases from other areas in the barn above that plane.

6.4.1 Contaminated barn area where C(H_2S) ≥ 50 ppm

Figure 6.37 to Figure 6.41 show the percentage of contaminated barn area overall and within each quintile for all pit-safety fan locations for Q_{ratio} 8, 15, 30, 60, and 120, respectively, for initial H_2S concentrations of 50, 100, and 500 ppm inside the manure pit. For all five Q_{ratios}, the overall barn area was never 100% contaminated, even when C_0 = 500 ppm. However, the overall barn area was 96% contaminated when C_0 = 500 ppm for pit-safety fan location (2,2) and Q_{ratio} 30.

There do not appear to be large differences between the cases with fan locations (1,1) and (1,2) and the case with no pit fan. These fan locations were so far from the inlet end of the barn that the pit-safety ventilation fan did not appear to have a large impact on the gas pushed up into the barn airspace at the inlet end when compared to the case with no pit fan. The difference in contaminated barn area overall and within each quintile between these two cases was less than 10% for all initial manure pit H_2S concentration values simulated from 50 to 500 ppm for Q_{ratio} 30, 60, and 120 (Figure 6.39, Figure 6.40, and Figure 6.41, respectively).
Figure 6.37. Contaminated area in the barn airspace where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8 with $C_0 = 50, 100,$ and $500$ ppm inside the manure pit.

Note: Error bars show $\pm 10\%$ of the value of each bar.
Figure 6.38. Contaminated area in the barn airspace where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr15 with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.39. Contaminated area in the barn airspace where $C(\text{H}_2\text{S}) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr30 with $C_0 = 50, 100, \text{ and } 500$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.40. Contaminated area in the barn airspace where $\text{C}(\text{H}_2\text{S}) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr60 with $C_0 = 50, 100$, and $500$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.41. Contaminated area in the barn airspace where $C(H_2S) \geq 50 \text{ ppm}$ during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr120 with $C_0 = 50, 100, \text{ and } 500 \text{ ppm}$ inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.42 shows the percentage of contaminated barn area in barn quintile I during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H$_2$S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile I was clear for all cases when C$_0$ = 50 ppm.
2. Quintile I was only 1% contaminated when C$_0$ = 100 ppm for pit-safety fan location (3,2) for Qr8, but was clear for all other cases when C$_0$ = 100 ppm.
3. Quintile I was never 100% contaminated for all cases when C$_0$ = 500 ppm.
Figure 6.42. Contaminated area in quintile I where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for $Q_{ratio}$ 8, 15, 30, 60, and 120, with $C_0 = 50, 100,$ and 500 ppm inside the manure pit.

Notes: Error bars show ±10% of the value of each bar; $Q_{ratio}$ 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.43 shows the percentage of contaminated barn area in barn quintile II during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile II was clear for all cases when $C_0 \leq 100$ ppm.
2. Quintile II was never 100% contaminated for all cases when $C_0 = 500$ ppm, but was 99% contaminated for pit-safety fan location (2,2) for Qr30.
3. There do not appear to be large differences in the percentage of contaminated area for pit-safety fan locations (1,1) and (1,2) at different $Q_{ratio}$ (the ±10% error bars overlap).
4. Contaminated area in quintile II increased as $Q_{ratio}$ decreased (pit-safety fan flow rate increased) for pit-safety fan location (2,2).
Figure 6.43. Contaminated area in quintile II where $C(\text{H}_2\text{S}) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for $Qr_{8, 15, 30, 60, \text{ and } 120}$, with $C_0 = 50, 100,$ and $500$ ppm inside the manure pit.

Notes: Error bars show ±10% of the value of each bar; $Qr_{8\text{ and } 15}$ were only used at fan locations (1,2) and (3,2).
Figure 6.44 shows the percentage of contaminated barn area in barn quintile III during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H$_2$S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile III was clear for all cases when $C_0 = 50$ ppm.

2. Quintile III was only 2% contaminated when $C_0 = 100$ ppm for pit-safety fan location (2,2) for Qr30, but was clear for all other cases when $C_0 = 100$ ppm.

3. Quintile III was never 100% contaminated for all cases when $C_0 = 500$ ppm, but was 92% contaminated for pit-safety fan location (2,2) for Qr30.

4. Quintile III was always clear for the case with no pit fan, even when $C_0 = 500$ ppm.

5. Quintile III was always clear for pit-safety fan location (1,1) for Qr30 and 120, but was 1% contaminated for Qr60 when $C_0 = 500$ ppm.

6. Quintile III was clear for pit-safety fan location (3,2) for Qr120, even when $C_0 = 500$ ppm.

7. Quintile III was $\leq 1\%$ contaminated for pit-safety fan location (1,2) for Qr15, 30, 60, and 120, but was 12.5% contaminated for Qr8 when $C_0 = 500$ ppm.
Figure 6.44. Contaminated area in quintile III where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for $Q_{ratio}$ 8, 15, 30, 60, and 120, with $C_0 = 50, 100, \text{and } 500$ ppm inside the manure pit.

Notes: Error bars show $\pm 10\%$ of the value of each bar; $Q_{ratio}$ 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.45 shows the percentage of contaminated barn area in barn quintile IV during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H$_2$S concentrations of 50, 100, and 500 ppm inside the manure pit. In general, it appeared that contaminated area increased as Q$_{ratio}$ decreased (pit-safety fan flow rate increased) for all fan locations. The following observations were made:

1. Quintile IV was clear for all cases when $C_0 = 50$ ppm.
2. Quintile IV was never 100% contaminated for all cases when $C_0 = 500$ ppm, but was 98% contaminated for pit-safety fan location (2,2) for Qr30.
3. Quintile IV was 11% contaminated for all pit-safety fan locations for Qr120 and the case with no pit fan when $C_0 = 100$ ppm.
4. There were no large differences in contaminated area for all fan pit-safety fan locations for Qr120 and the case with no pit fan when $C_0 = 500$ ppm (the ±10% error bars overlap).
Figure 6.45. Contaminated area in quintile IV where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for $Q_{ratio}$ 8, 15, 30, 60, and 120, with $C_0 = 50, 100,$ and 500 ppm inside the manure pit.

Notes: Error bars show ±10% of the value of each bar; $Q_{ratio}$ 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.46 shows the percentage of contaminated barn area in barn quintile V during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H2S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile V was never clear for all cases, even when $C_0 = 50$ ppm, with contaminated area ranging from 3.5 to 9.0%.
2. Quintile V was 100% contaminated for all cases when $C_0 \leq 100$ ppm.
Figure 6.46. Contaminated area in quintile V where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for $Qr_{8, 15, 30, 60,}$ and 120, with $C_0 = 50, 100,$ and 500 ppm inside the manure pit.

Notes: Error bars show ±10% of the value of each bar; $Qr_{8, 15}$ were only used at fan locations (1,2) and (3,2).
6.4.2 Duration of time when C(H₂S) ≥ 50 ppm

Figure 6.47 to Figure 6.51 show the duration of time the barn airspace was contaminated overall and within each quintile for all pit-safety fan locations for Qr8, 15, 30, 60, and 120, respectively, for initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. The term “overall” refers to the total barn area as a whole. Overall, the duration of contamination was greater than zero for all pit-safety fan locations and Q ratios when the initial manure pit concentration was 50 ppm. When C₀ = 100 ppm, the duration of contamination in the overall barn area was the same or decreased as Q ratio decreased (pit-safety fan flow rate increased) for pit-safety fan locations (1,1), (1,2), and (2,2), but the duration of contamination was the same or increased as Q ratio decreased for location (3,1). When C₀ = 500 ppm, the duration of contamination decreased as Q ratio decreased (pit-safety fan flow rate increased) for pit-safety fan locations (2,2), (3,1) and (3,2), but the overall barn area was contaminated for the full 300 s duration of pit-safety ventilation for pit-safety fan locations (1,1) and (1,2) for all flow rates and the case with no pit fan.
Figure 6.47. Duration of time in the barn airspace when $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8 with $C_0 = 50, 100,$ and $500$ ppm inside the manure pit.

Note: Error bars show $\pm 10\%$ of the value of each bar.
Figure 6.48. Duration of time in the barn airspace when $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr15 with $C_0 = 50, 100, \text{ and } 500$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.49. Duration of time in the barn airspace when $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr30 with $C_0 = 50, 100,$ and $500$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.50. Duration of time in the barn airspace when $C($H$_2$S$) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr60 with $C_0 = 50, 100, \text{ and } 500$ ppm inside the manure pit.

Note: Error bars show $\pm 10\%$ of the value of each bar.
Figure 6.51. Duration of time in the barn airspace when $\text{C(H}_2\text{S)} \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr120 with $C_0 = 50, 100,$ and $500$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.52 shows the duration of time the barn airspace was contaminated in quintile I during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile I was clear for all cases when \( C_0 = 50 \) ppm.
2. Quintile I was only contaminated for a duration of 1 s when \( C_0 = 100 \) ppm for pit-safety fan location (3,2) for Qr8, but was clear for all other cases when \( C_0 = 100 \) ppm.
3. Quintile I was never contaminated for the full 300 s duration for all cases when \( C_0 = 500 \) ppm.
4. The duration of contamination in quintile I decreased as \( Q_{ratio} \) decreased (pit-safety fan flow rate increased) for pit-safety fan locations (2,2), (3,1), and (3,2) when \( C_0 = 500 \) ppm.
5. There were no large differences in duration of contamination when \( C_0 = 500 \) ppm between the case with no pit fan and pit-safety fan locations (1,1) and (1,2) for all \( Q_{ratios} \) (the ±10% error bars overlap).
Figure 6.52. Duration of time in quintile I when $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for $Qr8$, 15, 30, 60, and 120, with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Notes: Error bars show ±10% of the value of each bar; $Qr_{ratio}$ 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.53 shows the duration of time the barn airspace was contaminated in quintile II during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H$_2$S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile II was clear for all cases when C$_0$ ≤ 100 ppm.
2. Quintile II was never contaminated for the full 300 s duration for all cases when C$_0$ = 500 ppm.
3. The duration of contamination in quintile II decreased as Q$_{\text{ratio}}$ decreased (pit-safety fan flow rate increased) for pit-safety fan locations (2,2), (3,1), and (3,2) when C$_0$ = 500 ppm.
4. The duration of contamination decreased for pit-safety fan location (1,2) from Qr120 to Qr60, but increased as Q$_{\text{ratio}}$ decreased (pit-safety fan flow rate increased) from Qr60 to Qr8.
Figure 6.53. Duration of time in quintile II when C(H2S) ≥ 50 ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, with C0 = 50, 100, and 500 ppm inside the manure pit.

Notes: Error bars show ±10% of the value of each bar; Qratio 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.54 shows the duration of time the barn airspace was contaminated in quintile III during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile III was clear for all cases when $C_0 = 50$ ppm.
2. Quintile III was only contaminated for a duration of 2 s when $C_0 = 100$ ppm for pit-safety fan location (2,2) for Qr30, but was clear for all other cases when $C_0 = 100$ ppm.
3. Quintile III was never contaminated for the full 300 s duration for all cases when $C_0 = 500$ ppm.
4. Quintile III was always clear for the case with no pit fan, even when $C_0 = 500$ ppm.
5. Quintile III was always clear for pit-safety fan location (1,1) for Qr30 and 120, but was contaminated for a duration of 20 s for Qr60 when $C_0 = 500$ ppm.
6. Quintile III was clear for pit-safety fan location (3,2) for Qr120, even when $C_0 = 500$ ppm.
7. Quintile III was contaminated for a duration of 10 s for pit-safety fan location (1,2) for Qr15, 30, 60, and 120, but was contaminated for a duration of 40 s for Qr8 when $C_0 = 500$ ppm.
Figure 6.54. Duration of time in quintile III when $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for $Qr_8, 15, 30, 60,$ and $120,$ with $C_0 = 50, 100,$ and $500$ ppm inside the manure pit.

Notes: Error bars show ±10% of the value of each bar; $Qr_{ratio} 8$ and $15$ were only used at fan locations (1,2) and (3,2).
Figure 6.55 shows the duration of time the barn airspace was contaminated in quintile IV during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H$_2$S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile IV was clear for all cases when $C_0 = 50$ ppm.
2. Quintile IV was never contaminated for the full 300 s duration for all cases when $C_0 = 500$ ppm.
3. Quintile IV was contaminated for a duration of 4 to 5 s for all pit-safety fan locations for Qr120 and the case with no pit fan when $C_0 = 100$ ppm.
4. Quintile IV was contaminated for a duration of 9 s for all pit-safety fan locations for Qr120 and the case with no pit fan when $C_0 = 500$ ppm.
Figure 6.55. Duration of time in quintile IV when C(H₂S) ≥ 50 ppm during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, with C₀ = 50, 100, and 500 ppm inside the manure pit.

Notes: Error bars show ±10% of the value of each bar; Q₉₈₈ 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.56 shows the duration of time the barn airspace was contaminated in quintile V during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with initial H\textsubscript{2}S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile V was never clear for all cases, even when C\textsubscript{0} = 50 ppm, with a duration of contamination ranging from 4 to 9 s.
2. Quintile V was never contaminated for the full 300 s duration for all cases when C\textsubscript{0} = 500 ppm.
Figure 6.56. Duration of time in quintile V when \( \text{C(H}_2\text{S)} \geq 50 \text{ ppm} \) during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, with \( C_0 = 50, 100, \) and 500 ppm inside the manure pit.

Notes: Error bars show \( \pm 10\% \) of the value of each bar; \( Q_{\text{ratio}} 8 \) and 15 were only used at fan locations (1,2) and (3,2).
6.4.3 Maximum $H_2S$ concentration in the barn during pit and barn ventilation

Figure 6.57 to Figure 6.61 show the maximum $H_2S$ concentration in the barn overall and within each quintile for all pit-safety fan locations for Qr8, 15, 30, 60, and 120, respectively, for an initial $H_2S$ concentration of 100 ppm inside the manure pit. These graphs are identical for all initial manure pit $H_2S$ concentrations simulated. The maximum concentration axis can be interpreted as the percentage of initial manure pit concentration, i.e. the overall maximum concentration in the barn for all fan locations was 100 ppm, or 100% of the initial concentration value $C_0 = 100$ ppm. Using the $C_0$ scaling method, the maximum concentration in quintile III of the barn for Qr30 at pit-safety fan location (2,2) with an initial manure pit $H_2S$ concentration of 500 ppm was $500 \times 0.59 = 295$ ppm.

It is clear from the graphs that the maximum concentration during pit-safety ventilation in tunnel ventilated barns occurs in quintile V. Pit-safety fan locations (1,1), (1,2), and (2,2) resulted in higher maximum concentrations in quintile IV than locations (3,1), (3,2), or the case with no pit fan. For Qr30, 60, and 120, pit-safety fan location (2,2) resulted in the highest maximum concentration in quintile III during pit-safety ventilation. Pit-safety fan locations (1,1) and (1,2) appeared similar to the case with no pit fan in quintiles I, II, and III for all Q$_{ratio}$ except Qr8, when the maximum concentration for fan location (1,2) in quintile III was greater than the case with no pit fan.
Figure 6.57. Maximum H$_2$S concentration in the barn airspace during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8 and C$_0$ = 100 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.58. Maximum H$_2$S concentration in the barn airspace during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr15 and C$_0$ = 100 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.59. Maximum H$_2$S concentration in the barn airspace during pit-safety ventilation for all TV simulation case pit-safety fan locations for $Q_r$30 and $C_0 = 100$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.60. Maximum H₂S concentration in the barn airspace during pit-safety ventilation for all TV simulation case pit-safety fan locations for QR60 and C₀ = 100 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 6.61. Maximum \( \text{H}_2\text{S} \) concentration in the barn airspace during pit-safety ventilation for all TV simulation case pit-safety fan locations for \( Q_{r120} \) and \( C_0 = 100 \) ppm inside the manure pit.

Note: Error bars show \( \pm 10\% \) of the value of each bar.

Figure 6.62 shows the maximum concentration in barn quintile I during pit-safety ventilation for all TV simulation case pit-safety fan locations for \( Q_{r8, 15, 30, 60, 120} \) with an initial \( \text{H}_2\text{S} \) concentration of 100 ppm inside the manure pit. \( Q_{r8} \) and 15 were only simulated at fan locations (1,2) and (3,2). There were no clear trends in quintile I, where the maximum concentration was below 40 ppm for all fan locations and \( Q_{r120} \) except \( Q_{r8} \), which raised the maximum concentration in Quintile I to 50 ppm at fan location (3,2).
Figure 6.62. Maximum H$_2$S concentration in barn quintile I during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, and manure pit $C_0 = 100$ ppm.

Note: Error bars show ±10% of the value of each bar; $Q_{ratio}$ 8 and 15 were only used at fan locations (1,2) and (3,2).

Figure 6.63 shows the maximum concentration in barn quintile II during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with an initial H$_2$S concentration of 100 ppm inside the manure pit. $Q_{ratio}$ Qr8 and 15 were only simulated at fan locations (1,2) and (3,2). There do not appear to be large differences or clear trends in maximum concentration versus $Q_{ratio}$ for fan locations (1,1), (1,2), and (3,2), where the
maximum concentration in quintile II was higher at Qr60 than Qr8, 15, 30, or 120. However, at fan locations (2,2) and (3,1) the maximum concentration in quintile II increased as Q_{ratio} decreased (pit-safety fan flow rate increased).

![Diagram showing maximum H$_2$S concentration in barn quintile II during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, and manure pit C$_0$ = 100 ppm.]

Figure 6.63. Maximum H$_2$S concentration in barn quintile II during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, and manure pit C$_0$ = 100 ppm.

Notes: Error bars show ±10% of the value of each bar; Q_{ratio} 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.64 shows the maximum concentration in barn quintile III during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with an initial H₂S concentration of 100 ppm inside the manure pit. Q$_{ratio}$ Qr8 and 15 were only simulated at fan locations (1,2) and (3,2). There do not appear to be clear trends in maximum concentration versus Q$_{ratio}$ in quintile III. However, fan location (2,2) had the highest maximum concentration in quintile III at Qr30, 60, and 120.

Figure 6.64. Maximum H₂S concentration in barn quintile III during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, and manure pit C$_0$ = 100 ppm.

Notes: Error bars show ±10% of the value of each bar; Q$_{ratio}$ 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.65 shows the maximum concentration in barn quintile IV during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with an initial H₂S concentration of 100 ppm inside the manure pit. Q\textsubscript{ratio} Qr8 and 15 were only simulated at fan locations (1,2) and (3,2). There do not appear to be large differences in maximum concentration versus Q\textsubscript{ratio} in quintile IV. However, the maximum concentration in quintile IV increases as Q\textsubscript{ratio} decreases (pit-safety fan flow rate increases) for all pit-safety fan locations.

Figure 6.65. Maximum H₂S concentration in barn quintile IV during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, and manure pit

\[ C_0 = 100 \text{ ppm.} \]

Notes: Error bars show ±10% of the value of each bar; Q\textsubscript{ratio} 8 and 15 were only used at fan locations (1,2) and (3,2).
Figure 6.66 shows the maximum concentration in barn quintile V during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120 with an initial H₂S concentration of 100 ppm inside the manure pit. The maximum concentration in quintile V was 100 ppm (or 100% of the initial concentration in the manure pit) for all fan locations and Q\text{ratios}.

Figure 6.66. Maximum H₂S concentration in barn quintile V during pit-safety ventilation for all TV simulation case pit-safety fan locations for Qr8, 15, 30, 60, and 120, and manure pit

\[ C_0 = 100 \text{ ppm} \]

Notes: Error bars show ±10% of the value of each bar; Q\text{ratio} 8 and 15 were only used at fan locations (1,2) and (3,2).
6.4.4 $T_{pel}$ versus $Q_{ratio}$

This section compares the simulated $T_{pel}$ times for the TV cases (pit-safety fan locations and $Q_{ratios}$) to the case with no pit fan. Figure 6.67 shows the duration of ventilation required to reach a maximum $H_2S$ concentration of 10 ppm ($T_{pel}(10)$) everywhere inside the manure pit from an initial $H_2S$ concentration of 100 ppm for all TV simulation cases. It is clear from the graph that the cases with pit-safety fan locations (1,1) and (1,2) required more time to reach $T_{pel}(10)$ inside the manure pit than the case with no pit fan. However, all three $Q_{ratios}$ for the cases with pit-safety fan location (1,1), and $Qr120$ and $Qr30$ for the case with pit-safety fan location (1,2) required within 10% of the $T_{pel}(10)$ time of the case with no pit safety fan. For the case with pit-safety fan location (1,2), $Qr60$, $Qr15$, and $Qr8$ required an additional 10% or greater duration of time than the case with no pit safety fan.
Figure 6.67. $T_{\text{pel}}(10)$ vs. $Q_{\text{ratio}}$ for TV simulation cases with $C_0 = 100$ ppm.

Notes: Error bars show ±10% of the value of each bar; $Q_{\text{ratio}}$ 8 and 15 were only used at fan locations (1,2) and (3,2).

It was expected that $T_{\text{pel}}$ times would decrease as $Q_{\text{ratio}}$ decreased (pit-safety fan flow rate increased) because increased pit-safety fan flow rates should result in increased air exchange rates in the manure pit, displacing the gas in the pit airspace in a shorter duration of time with ducted atmospheric air. In general, it appears that as $Q_{\text{ratio}}$ decreased (pit-safety fan flow rate increased), $T_{\text{pel}}(10)$ decreased for pit-safety fan locations (2,2), (3,1), and (3,2). Simulations for these fan
locations reached $T_{pel}(10)$ in less than half the time required for the case with no pit safety fan. However, the opposite trend was observed for pit-safety fan locations (1,1) and (1,2), where $T_{pel}(10)$ increased as $Q_{ratio}$ decreased (pit-safety fan flow rate increased). Locations (1,1) and (1,2) were counterflow cases, where the bulk direction of airflow in the manure pit was opposite that of the barn airspace above. In these counterflow cases, the pit-safety fan starts to cancel out the effects of the barn exhaust fans drawing air into the far end of the pit, creating semi-stagnant regions where the pit gas is either exposed to very low air velocities or gets entrained in vortices inside the pit. This slows the rate of convective air exchange, and diffusion takes over, leading to much longer $T_{pel}$ times. A similar phenomenon occurs when outdoor wind blows against walls containing barn exhaust fans, effectively canceling out the barn air flow. Pit-safety ventilation should not be performed when a strong wind is blowing against the barn exhaust fans.

Figure 6.68 shows the duration of ventilation required to reach a maximum $H_2S$ concentration of 1 ppm ($T_{pel}(1)$) everywhere inside the manure pit from an initial $H_2S$ concentration of 100 ppm for all TV simulation cases. Trends are similar to those seen in Figure 6.67, except at location (1,1) for $Q_{ratio}$ 60 which reached $T_{pel}(1)$ 10 seconds sooner than the case with no pit safety fan.
Figure 6.68. $T_{pel}(1)$ vs. $Q_{ratio}$ for TV simulation cases with $C_0 = 100$ppm.

Notes: Error bars show ±10% of the value of each bar; $Q_{ratio}$ 8 and 15 were only used at fan locations (1,2) and (3,2).
### 6.4.5 Predicting initial concentration that results in $\text{C}(\text{H}_2\text{S}) \geq 50$ ppm in each quintile

The maximum concentration on the measurement plane located 0.15 m (6 in.) above the slotted floor in each barn quintile is a linear function of initial manure pit concentration. This means for each pit-safety fan location and flow rate it is possible to predict the initial concentration that will result in $\text{C}(\text{H}_2\text{S}) \geq 50$ ppm in each barn quintile. The maximum concentration on the measurement plane anywhere in the barn is simply equal to the largest maximum value in any quintile.

Using the $C_0$ scaling method from Chapter 5, the maximum concentration in each barn quintile can be predicted from the maximum concentration when $C_0 = 100$ ppm. For example, the tunnel ventilated No Pit Fan case had maximum $\text{H}_2\text{S}$ concentrations of 100 ppm, 71 ppm, 9 ppm, 22 ppm, and 33 ppm in barn quintiles V, IV, III, II, and I, respectively, when the initial manure pit $\text{H}_2\text{S}$ concentration was 100 ppm. Scaling each maximum value by $C_0$ shows that the maximum concentrations in barn quintiles V, IV, III, II, and I were 100%, 71%, 9%, 22%, and 33%, respectively, of the initial concentration in the manure pit. Dividing the barn contamination threshold value of 50 ppm by these percentages yields the initial manure pit concentration that will result in $\text{C}(\text{H}_2\text{S}) \geq 50$ ppm in each quintile of the barn:

\[
\begin{align*}
50 \text{ ppm} / 1.00 &= 50 \text{ ppm for Quintile V} \\
50 \text{ ppm} / 0.71 &= 70 \text{ ppm for Quintile IV} \\
50 \text{ ppm} / 0.09 &= 556 \text{ ppm for Quintile III} \\
50 \text{ ppm} / 0.22 &= 227 \text{ ppm for Quintile II} \\
50 \text{ ppm} / 0.33 &= 152 \text{ ppm for Quintile I}
\end{align*}
\]

Table 6.32 lists the initial manure pit $\text{H}_2\text{S}$ concentration that results in $\text{C}(\text{H}_2\text{S}) \geq 50$ ppm in each barn quintile for each TV simulation case and $Q_{\text{ratio}}$. 

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Table 6.32. Initial manure pit H$_2$S concentration (ppm) that results in C(H$_2$S) $\geq$ 50 ppm in each quintile during pit-safety ventilation for tunnel ventilated barn simulation cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Q$_r$</th>
<th>C$_0$ (ppm) that results in C(H$_2$S) $\geq$ 50 ppm in Barn Quintile</th>
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<td></td>
<td>8</td>
<td>50</td>
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<tr>
<td>No Fan</td>
<td>-</td>
<td>50</td>
</tr>
</tbody>
</table>

6.4.6 Keeping animals in tunnel ventilated barns during pit-safety ventilation

Ultimately, the decision to remove animals from the barn during manure pit-safety ventilation events will be up to the facility owner. This discussion is framed in the context of the OSHA regulation that allows a maximum human exposure level of 50 ppm for a duration up to 10 minutes based on the assumption that no prior exposure has occurred during the day. This discussion may not be valid for stricter exposure limits such as those specified by NIOSH or
ACGIH, but the procedures used to analyze the simulation results for an \text{H}_2\text{S} gas exposure limit of 50 ppm can be applied to other threshold values. There are no established safe exposure limits to \text{H}_2\text{S} gas for animals in confinement housing.

Confinement of animals within certain areas of a barn will depend on the initial \text{H}_2\text{S} gas concentration inside the manure pit, the pen layout or availability of temporary pen dividers, and the number of animals that can safely be kept in the reduced pen area for a short duration of time. Nearly all pit-safety fan locations and \text{Q}_{\text{ratio}}s, and the case with no pit safety fan resulted in contiguous clear areas where \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) for all simulated initial \text{H}_2\text{S} gas concentrations inside the manure pit. The exceptions where clear area was not contiguous occurred for cases TV22 \text{Qr30} when \( C_0 \geq 100 \text{ ppm} \), TV22 for \text{Q}_{\text{ratio}}s 60 and 120 when \( C_0 \geq 200 \text{ ppm} \), TV32 \text{Qr60} when \( C_0 \geq 400 \text{ ppm} \), and TV32 \text{Qr120} when \( C_0 \geq 300 \text{ ppm} \).

For tunnel ventilated barns with initial manure pit \text{H}_2\text{S} concentrations of 100 ppm or less, fan locations (1,1), (1,2), (3,1), and (3,2) resulted in contiguous clear areas in quintiles I, II, and III, and part of quintile IV. These cases had at least 75\% of the barn area that was contiguous and clear during pit and barn ventilation events for \text{Qr30}, \text{Qr60}, and \text{Qr120}, and 70\% or better for \text{Qr8} and \text{Qr15}. When \( C_0 = 200 \text{ ppm} \), 59\% to 72\% of contiguous barn area had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \). When \( C_0 = 300 \text{ ppm} \), 43\% to 62\% of contiguous barn area had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \). When \( C_0 = 400 \text{ ppm} \), 36\% to 60\% of contiguous barn area had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \). However, when \( C_0 = 500 \text{ ppm} \), only 28\% to 57\% of contiguous barn area had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \).

For tunnel ventilated barns, if the pens are located in the center of the barn, with alleys along the side walls, pit-safety ventilation fan location (3,2) and \text{Qr30} might be useful in quintiles I, II, and III since the contaminated areas in those quintiles were limited to the side walls of the barn for manure pit \text{H}_2\text{S} \( C_0 \leq 500 \text{ ppm} \). \text{Qr60} resulted in clear areas in all of quintile III and the center portion of quintile II when the manure pit \text{H}_2\text{S} \( C_0 \leq 500 \text{ ppm} \) (the center of quintile I was clear for \( C_0 \leq 300 \text{ ppm} \)). However, for \text{Qr120} only quintile III was clear for manure pit \text{H}_2\text{S} \( C_0 \leq 500 \text{ ppm} \).
This discussion is for a specific barn size and ventilation configuration. Other barn sizes and ventilation configurations may result in clear zones large enough to safely relocate animals temporarily during pit and barn ventilation events. While some of the tunnel ventilated barn simulation cases resulted in clear regions within the barn, in practice it could be difficult to corral all of the animals into those areas. Also, all of these simulation cases had uniform initial conditions inside the manure pit. In reality, it is more likely that the initial gas concentration distribution would be non-uniform.

6.4.7 Hypothesis discussion

The results from the TV simulation cases are discussed in this section in the context of the research hypotheses from Chapter 2. When the hypotheses were first drafted, it was thought that careful selection of pit-safety ventilation fan location and flow rate might be able to prevent contamination of the barn airspace during manure pit and barn ventilation events. However, the simulation results show that contamination of portions of the barn airspace occurs even when no pit safety fan is used. The hypotheses are restated here for clarity.

\( H_0: \) For a given initial concentration of \( \text{H}_2\text{S} \) gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate (\( \text{m}^3/\text{s} \)), there is no positive pressure pit-safety ventilation air flow rate (\( \text{m}^3/\text{s} \)) that will result in dangerous conditions (\( C(\text{H}_2\text{S}) \geq 50 \text{ ppm} \) for 10 min) in selected contiguous barn areas when the initial pit concentration is greater than 50 ppm.

For null hypothesis (\( H_0 \)) testing, the rejection region is everything outside the graph of \( C(\text{H}_2\text{S}) > 50 \text{ ppm} \) for 10 minutes. So, for discussion purposes, if barn quintiles had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) during pit-safety ventilation, then we must reject \( H_0 \). The “10 minute” criterion did not need
to be considered when discussing \( H_0 \) below because the quintiles that had durations of contamination for the full 300 s of pit-safety ventilation also had maximum concentrations greater than 50 ppm and therefore fell outside the rejection region. Another region that might be considered is the OSHA ceiling limit of 20 ppm for 8 hours, but few of the simulation cases had quintiles where \( C(H_2S) < 20 \) ppm when the initial manure pit \( H_2S \) gas concentration was 50 ppm or greater, and the concentration in all of those cases would have decayed to zero in far less than 8 hours.

1. For all TV pit-safety fan locations and \( Q_{ratios} \) and the case with no pit safety fan, all quintiles had \( C(H_2S) \leq 50 \) ppm during pit-safety ventilation when the initial \( H_2S \) gas concentration inside the manure pit was 50 ppm. The duration of time when \( C(H_2S) = 50 \) ppm was 9 seconds or less in quintile V. The \( H_2S \) concentration in quintiles I, II, III, and IV never reached 50 ppm.

2. For all TV pit-safety fan locations and \( Q_{ratios} \) and the case with no pit safety fan, quintiles I, II, III, and IV had \( C(H_2S) \leq 50 \) ppm during safety pit-safety ventilation when the initial \( H_2S \) gas concentration inside the manure pit was 51 ppm, but \( H_0 \) should be rejected for quintile V because the maximum concentration was 51 ppm. The duration of time when \( C(H_2S) \geq 50 \) ppm was 14 seconds or less in quintile V.

3. When the initial manure pit \( H_2S \) gas concentration was 55 ppm, quintile IV had a maximum \( H_2S \) concentration of 54 ppm for case TV12 Qr8. For all other TV pit-safety fan locations and \( Q_{ratios} \) and the case with no pit safety fan, quintiles I, II, III, and IV had \( C(H_2S) \leq 50 \) ppm during safety pit-safety ventilation when the initial \( H_2S \) gas concentration inside the manure pit was 55 ppm, but \( H_0 \) should be rejected for quintile V because the maximum concentration was 55 ppm. The duration of time when \( C(H_2S) \geq 50 \) ppm was 25 seconds or less in quintile V.
4. For all TV pit-safety fan locations and $Q_{\text{ratios}}$ and the case with no pit safety fan, quintiles I, II, and III had $C(H_2S) \leq 50$ ppm during safety pit-safety ventilation when the initial $H_2S$ gas concentration inside the manure pit was 75 ppm, but $H_0$ should be rejected for quintiles IV and V because the maximum concentration in those quintiles was greater than 50 ppm. The duration of time when $C(H_2S) \geq 50$ ppm was 13 seconds or less in quintile IV, and 40 seconds or less in quintile V.

5. For nearly all TV pit-safety fan locations and $Q_{\text{ratios}}$ and the case with no pit safety fan, quintiles I, II, and III were clear when $C_0 \leq 100$ ppm. There was one exception: when $C_0 = 100$ ppm, the maximum $H_2S$ concentration in quintile III was 59 ppm for a duration of 2 s for case TV22 Qr30.

6. For nearly all TV pit-safety fan locations and $Q_{\text{ratios}}$ and the case with no pit safety fan, quintile IV was clear when $C_0 \leq 55$ ppm. There was one exception, when $C_0 = 55$ ppm, the maximum $H_2S$ concentration in quintile IV was 54 ppm for a duration of 2 s for case TV12 Qr8.

7. For all TV pit-safety fan locations and $Q_{\text{ratios}}$ and the case with no pit safety fan, Quintile V was only clear when $C_0 \leq 50$ ppm.

8. For all TV pit-safety fan locations and $Q_{\text{ratios}}$ and the case with no pit safety fan, quintile II was never clear when $C_0 > 200$ ppm. When $C_0 = 200$ ppm, quintile II was only clear for cases TV11 for $Q_{\text{ratio}}$ 30 and 120, TV12 for all $Q_{\text{ratio}}$, and the case with no pit fan. The maximum $H_2S$ concentration in quintile II was 53 ppm for a duration of 20 s for case TV11 Qr60.

9. When $C_0 = 200$ ppm, quintile III was clear for nearly all pit-safety fan locations and $Q_{\text{ratios}}$ and the case with no pit safety fan. The exceptions were cases TV22 for all $Q_{\text{ratios}}$, and case TV32 for Qr15.
10. When $C_0 = 300$ ppm, quintile III was clear for all $Q_{\text{ratio}}$ for cases TV11, TV12, TV31, and the case with no pit safety fan. Quintile III was only clear for case TV32 for $Q_{\text{ratio}}$ 30 and 60.

11. When $C_0 = 400$ ppm, quintile III was clear for all $Q_{\text{ratio}}$ for case TV11. Quintile III was only clear for case TV12 for $Q_{\text{ratio}}$ 15, 30, 60, and 120. Quintile III was only clear for cases TV31 and TV32 for $Q_{\text{ratio}}$ 60 and 120. Quintile III was clear for the case with no pit safety fan.

12. When $C_0 = 500$ ppm, quintile III was only clear for cases TV11 for $Q_{\text{ratio}}$ 30 and 120, case TV32 for $Q_{\text{r120}}$, and the case with no pit safety fan.

$H_1$: For a given initial concentration of H$_2$S gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate (m$^3$/s), there exists a maximum pit air ventilation flow rate (m$^3$/s) that can be used without raising the concentration of H$_2$S gas in selected contiguous barn areas (measured at 0.15 m (6 in.) above the floor) above a threshold level of 50 ppm ($C(H_2S) \geq 50$ ppm for 10 min), yet will evacuate the gas inside the pit within 30 minutes.

$H_2$: For a given initial concentration of H$_2$S gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate (m$^3$/s), there exists a minimum effective pit-safety ventilation air flow rate (m$^3$/s) that will result in $T_{\text{pel}}$ (10 ppm) being reached in a defined acceptable maximum amount of time (30 minutes, or another preselected reasonable time limit) without creating dangerous conditions ($C H_2S \geq 50$ ppm for 10 min) in selected contiguous barn areas (measured at 0.15 m (6 in.) above the floor).

Alternate hypotheses $H_1$ and $H_2$ deal with reaching $T_{\text{pel}}$ inside the manure pit within 30 minutes for cases that resulted in quintiles where $C(H_2S) \leq 50$ ppm inside the barn during pit-
safety ventilation and \( H_0 \) was rejected. So, for discussion purposes, if quintiles had \( C(H_2S) \leq 50 \) ppm during pit-safety ventilation and \( H_0 \) was rejected, we must only reject \( H_1 \) or \( H_2 \) if \( T_{pel} > 30 \) minutes.

1. For all TV pit-safety fan locations and \( Q_{ratio} \) and the case with no pit safety fan, \( T_{pel}(10 \) ppm) was reached in less than 30 minutes. The only case that required longer than 30 minutes to reach \( T_{pel}(1 \) ppm) was TV12 Qr8 when the initial manure pit \( H_2S \) concentration was 400 ppm or greater. However, there were no areas where \( C(H_2S) \leq 50 \) ppm within the barn during pit-safety ventilation, so we cannot evaluate \( H_1 \) or \( H_2 \) for those cases.

### 6.5 Conclusions for tunnel ventilated barn simulations

The purpose of this chapter was to identify zones within tunnel ventilated barns with fully-slotted floors located above full-sized mechanically-ventilated manure pits that must be evacuated for ratios of \( Q_{pit}/Q_{barn} \) that result from pit gases being exhausted into the barn airspace. A series of CFD simulations was performed with different pit-safety ventilation fan locations and flow rates to investigate how these factors affect the area and duration of time when the barn airspace is contaminated with \( C(H_2S) \geq 50 \) ppm and the maximum \( H_2S \) concentration on the barn measurement plane during pit and barn ventilation. Pit-safety fan locations (1,1) and (1,2) were counterflow configurations, (2,2) was in the center of the barn, and (3,1) and (3,2) were parallel flow configurations. The conclusions stated in this section are only valid for the specific tunnel ventilated barn configuration, manure pit-safety fan locations and \( Q_{ratio} \), and initial manure pit \( H_2S \) concentrations used in this study.
6.5.1 Conclusions

1. Manure pit-safety fan location, $Q_{\text{ratio}}$, and initial $H_2S$ concentration in the manure pit influence the contaminated barn area, duration of contamination, maximum $H_2S$ concentration in the barn airspace, and the duration of time required to reach $T_{pel}$ in the manure pit for tunnel ventilated barns during manure pit-safety ventilation.

2. There were large, contiguous areas in the barn that were not contaminated during manure pit-safety ventilation across nearly all fan locations, $Q_{\text{ratio}}$, and initial manure pit $H_2S$ gas concentrations.

3. The maximum concentration in the barn airspace in tunnel ventilated barns during pit-safety ventilation was equal to the initial manure pit $H_2S$ concentration in quintile V for all fan locations and $Q_{\text{ratio}}$, therefore animals should be evacuated from at least portions of quintile V of tunnel ventilated barns when $C_0 \geq 50$ ppm.

4. For all pit-safety fan locations, when the initial manure pit $H_2S$ gas concentration was 100 ppm or less, at least 75% of contiguous barn area had $C(H_2S) \leq 50$ ppm during pit-safety ventilation for $Qr_{30}$, $Qr_{60}$, and $Qr_{120}$, and 70% or better for $Qr_8$ and $Qr_{15}$.

5. When $C_0 = 200$ ppm, 59% to 72% of contiguous barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratio}}$.

6. When $C_0 = 300$ ppm, 43% to 62% of contiguous barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratio}}$.

7. When $C_0 = 400$ ppm, 36% to 60% of contiguous barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratio}}$.

8. When $C_0 = 500$ ppm, only 28% to 57% of contiguous barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratio}}$.

9. The difference in contaminated area in the barn overall and in each quintile was less than 10% for all $Q_{\text{ratio}}$ and initial concentrations between fan locations (1,1) and (1,2).
10. Pit-safety fan locations (1,1) and (1,2) resulted in longer $T_{pel}$ times with similar contamination area and durations of time when $C(H_2S) \geq 50$ ppm in the barn airspace when compared to the case with no pit safety fan, making counterflow pit-safety fan locations undesirable for tunnel ventilated barns.

11. When $C_0 \geq 200$ ppm, location (2,2) resulted in more contaminated area in the barn overall and in quintiles II, III, and IV than all other cases as well as the case with no pit safety fan, making this the worst choice for pit-safety ventilation fan location for tunnel ventilated barns.

12. When $C_0 \geq 200$ ppm, location (3,2) (parallel flow with the pit-safety fan located along the longitudinal barn centerline) resulted in less overall contaminated area in the barn than all other cases as well as the case with no pit safety fan, making this the best choice for pit-safety ventilation fan location for tunnel ventilated barns.
Chapter 7

Phase III Cross-Ventilated Barn Simulations

7.1 Introduction

This chapter describes simulations that were performed for a 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long) mechanically cross-ventilated (CV) barn located above a full-sized manure pit with a fully-slotted cover. Manure pit-safety ventilation fan configuration (location and flow rate) was varied to simulate the resulting distribution of H$_2$S gas in the barn airspace during a barn and manure pit-safety ventilation event. Simulation results for each pit-safety fan configuration were analyzed to determine the affected area in the barn and the duration of time when the concentration of H$_2$S gas was 50 ppm or greater, the maximum H$_2$S concentration in the barn airspace, and how much time was required to reach T$_{p1}$ in the manure pit. The purpose of this chapter was to identify zones within mechanically cross-ventilated barns with fully-slotted floors located above full-sized mechanically-ventilated manure pits that must be evacuated for ratios of manure pit to barn ventilation air flow rates (Q$_{pit}$/Q$_{barn}$) that result in pit gases being exhausted into the barn airspace.
7.2 Methodology

CFD simulations were performed for a mechanically cross-ventilated barn located above a full-sized manure pit with a fully-slotted cover. The same CFD model parameters and settings were used for the cross-ventilated barn model as for the Phase II tunnel ventilated barn model described in section 6.2.6. The fully-slotted floor was represented using the same porous media described in section 6.2.6.7. The only differences in the model were the locations and configuration of the cross-ventilated barn exhaust fans and barn inlet slots, and the $Q_p$ and $Q_b$ air flow rates.

7.2.1 Pit and barn details and dimensions

The cross-ventilated barn and manure pit had the same overall dimensions as the tunnel ventilated cases. For cross-ventilated buildings, a width of 12.20 m (40 ft) is a practical limit for being able to effectively ventilate the barn using common ventilation fan and ceiling inlet slot configurations only at the eaves. The manure pit underneath the barn had the same length and width dimensions as the barn with a depth of 2.44 m (8 ft). Only fully slotted floors were considered.

The same $Q_p/Q_b$ ratios were utilized as for the tunnel ventilated cases (Qr30, 60, and 120), but the barn air flow rate, $Q_b$, was based the hot weather maximum ventilation rate for the selected building size and design animal stocking density. The pit-safety ventilation air flow rate, $Q_p$, was calculated from $Q_b$ and the ratio of $Q_p/Q_b$ used for each pit and barn configuration. Design calculations for ventilation requirements based on hot weather maximum ventilation rates for the selected barn size and number of animals can be found in Appendix A.
Details and critical dimensions for the selected pit and barn configurations are listed below:

1. Barn inside dimensions: 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long)
2. Height to barn ceiling: 3.05 m (10 ft)
3. Full-sized pit dimensions: same width and length as barn above, 2.44 m (8 ft) depth.
4. Pit cover and slot dimensions: 0.15 m (6 in.) thick cover, fully-slotted with 50.8 mm (2.0 in.) slot width and 0.15 m (6 in.) slat width, with slots orientated perpendicular to the length of the barn.
5. Pit/barn limitations: It was assumed that 0.15 m (6 in.) or less of manure remained in the storage prior to ventilation and entry (no source of H₂S gas); no foaming; no agitation; no dividers, support columns, or other obstructions were present in the pit.
6. Cross-ventilated barn walls:
   a. Sidewall inlet opening slot width: 0.15 m (6.0 in.) for both sidewalls
   b. Sidewall fan layout: Three 1.27 m (50 in.) diameter outlet fans spaced 10.16 m (33.3 ft) on-center, with each fan centered at each 1/3 of the barn length. Fan centerlines located 1.2 m (48 in.) above barn floor (Figure 7.1).
   c. End wall layout: Totally enclosed end walls.
7. The barn floor was 0.15 m (6 in.) thick, and this was placed between the pit and barn so that the overall distance from the pit floor to the barn ceiling was 5.64 m (18.5 ft).
8. The influence of animals on airflow in the barn was ignored for this first study of barn contamination during positive pressure safety ventilation of manure pits.
Figure 7.1. Sidewall fan layout schematic for cross-ventilated barn.

Figure 7.2 shows the full range of pit-safety fan locations used for Phase III of the research project. Simulations performed using these fan locations cover most real-world scenarios that might be encountered when ventilating a manure pit located beneath barns without pump-out ports around the building perimeter. Additionally, the results from simulations with fans at these locations should provide insight about the behavior of fans placed at intermediate locations.

In the CV barn simulation cases, the X-axis is defined as the centerline across the width of the barn, which is also the line of symmetry. Due to symmetry conditions that exist in the barn, it was not necessary to simulate the locations indicated in Figure 7.2 by dashed red circles in the negative Y-direction. Table 7.1 lists the X and Y coordinates for the five pit-safety ventilation fan locations used.
Figure 7.2. Fan locations used for the cross-ventilated barn with a full-sized manure pit.

<table>
<thead>
<tr>
<th>Fan Location</th>
<th>Fan X m (ft)</th>
<th>Fan Y m (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,1</td>
<td>10.97 m (36.0 ft)</td>
<td>14.02 m (46.0 ft)</td>
</tr>
<tr>
<td>1,3</td>
<td>1.22 m (4.0 ft)</td>
<td>14.02 m (46.0 ft)</td>
</tr>
<tr>
<td>2,1</td>
<td>10.97 m (36.0 ft)</td>
<td>0.00 m (0.0 ft)</td>
</tr>
<tr>
<td>2,2</td>
<td>6.10 m (20.0 ft)</td>
<td>0.00 m (0.0 ft)</td>
</tr>
<tr>
<td>2,3</td>
<td>1.22 m (4.0 ft)</td>
<td>0.00 m (0.0 ft)</td>
</tr>
</tbody>
</table>

*Fan X and Y coordinates are with respect to the origin shown on Figure 7.2. (0,0) is along the longitudinal centerline at the inlet end of the barn.
7.2.2 Simulation case naming convention

A naming convention was used for all simulation cases performed for the cross-ventilated barns. The simulation case CV23Qr30 denotes the simulation was for a fully-slotted pit cover, a full-sized pit, with a cross-ventilated barn located above, with the pit-safety fan at location (2,3), and Qr30 represents a pit-safety fan flow rate 1/30 that of the barn exhaust fans. A breakdown is shown below, followed by abbreviation definitions:

CV 23 Qr30

Where:

CV = Cross-ventilated barn

23 = Pit-safety fan Location (2,3) – Figure 7.2

Qr30 = Fan case for $Q_p/Q_b$ ratio 1/30

Simulation cases were also conducted with no pit-safety ventilation fan as a baseline for fan location and flow rate comparisons. For the cases where no pit-safety ventilation fan was used, “No Fan” appears instead of an abbreviation.
7.2.3 Schedule of simulations

A list of the simulations run for Phase III of this study is presented in Table 7.2. The table lists the fan cases ($Q_r$), the corresponding $Q_p/Q_b$ ratio, and the actual pit-safety ventilation fan flow rate ($Q_p$) simulated at each pit-safety fan location in the barn.

Table 7.2. Schedule of simulations run for phase iii cross-ventilated barn model.

| Case   | $Q_r$ | $Q_p/Q_b$ | $Q_p$  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CV11</td>
<td>120</td>
<td>1/120</td>
<td>0.2 m$^3$/s (500 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>0.5 m$^3$/s (1,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>0.9 m$^3$/s (2,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>1/120</td>
<td>0.2 m$^3$/s (500 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>0.5 m$^3$/s (1,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>0.9 m$^3$/s (2,000 cfm)</td>
</tr>
<tr>
<td>CV21</td>
<td>120</td>
<td>1/120</td>
<td>0.2 m$^3$/s (500 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>0.5 m$^3$/s (1,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>0.9 m$^3$/s (2,000 cfm)</td>
</tr>
<tr>
<td>CV22</td>
<td>120</td>
<td>1/120</td>
<td>0.2 m$^3$/s (500 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>0.5 m$^3$/s (1,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>0.9 m$^3$/s (2,000 cfm)</td>
</tr>
<tr>
<td>CV23</td>
<td>120</td>
<td>1/120</td>
<td>0.2 m$^3$/s (500 cfm)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1/60</td>
<td>0.5 m$^3$/s (1,000 cfm)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1/30</td>
<td>0.9 m$^3$/s (2,000 cfm)</td>
</tr>
<tr>
<td>No Fan</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: $Q_b$ for all CV cases was 28.3 m$^3$/s (60,000 cfm).
7.2.4 Phase III CFD model

The cross-ventilated barn was represented by a thin 3D shell with closed ends (normal to the direction of barn airflow), two sidewall slot openings representing the fresh air inlets, and one sidewall with fan openings representing the outlets for the barn ventilation fans (Figure 7.3).

Figure 7.3. CFD model for the cross-ventilated barn.

7.2.5 CFD model settings

The general settings used in SWFS for the CFD models for both the tunnel ventilated and cross-ventilated barns are listed in section 6.2.6. Only the specific settings that were different for the cross-ventilated barns are described in this section.

7.2.5.1 Goals and convergence criteria

All simulations were run until the maximum volume fraction of \( \text{H}_2\text{S} \) gas inside the manure pit decayed to less than 1.0 ppm with an initial concentration of 100 ppm. A few cases were extended until the maximum volume fraction of \( \text{H}_2\text{S} \) gas inside the manure pit decayed to
less than 0.2 ppm to ensure that multiplying the results by a factor of 5 (to represent an initial pit concentration of 500 ppm) would have a value for $T_{pel}$ at a final concentration of 1 ppm inside the pit.

Because the simulation was transient, all other convergence criteria, called goals in SWFS, were only used to track the values of solution variables during the calculations. Global average values for pressure, turbulent energy, turbulent dissipation, velocity (magnitude, in the X, Y, and Z directions), and mass of fluid were saved at each 0.25 second interval of the simulation. The global average and maximum volume fraction of hydrogen sulfide gas were also saved.

For the barn airspace, a plane located 0.15 m (6 in.) above the barn floor was selected as the threshold height used to determine if toxic levels of H$_2$S gas were being evacuated into the barn airspace above the manure storage during ventilation. The 0.15 m (6 in.) height was selected to consider the breathing space of piglets, which are the smallest animals typically confined inside a barn located above a confined-space manure storage. Point parameters were used to track H$_2$S concentrations at 1,000 point locations on the measurement plane located 0.15 m (6 in.) above the barn floor plane (Figure 7.4).
Figure 7.4. CV barn model with 1,000 grid points placed on the 0.15 m (6 in.) barn measurement plane.
7.2.5.2 Cross-ventilated barn exhaust fans

The CV barn fans were represented by an outlet velocity boundary condition applied to the interior surface of a lid that was placed over the fan openings in the outlet side wall of the model (Figure 7.5).

Figure 7.5. Schematic of the CV barn model and boundary conditions.
7.2.5.3 Pit-safety ventilation fan

Ducted fresh air was assumed for the pit-safety ventilation fan inlet, but no solid geometry was included in the CFD model to represent the inlet air ducting. The pit-safety ventilation fan was modeled in the same manner as for the tunnel ventilated barn model, described in Section 6.2.6.6. The pit-safety fan diameters used for the cross-ventilated simulation cases are listed in Table 7.3.

Table 7.3. Pit-safety ventilation fan diameters used for Cross-Ventilated barn cases.

<table>
<thead>
<tr>
<th>Fan Case</th>
<th>$Q_{\text{barn}}$ m$^3$/s (cfm)</th>
<th>$Q_p/Q_b$ ratio</th>
<th>$V$ m/s (ft/s)</th>
<th>$Q_{\text{pit}}$ m$^3$/s (cfm)</th>
<th>$A$ m$^2$ (ft$^2$)</th>
<th>Dia. m (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qr30</td>
<td>28.32 (60,000)</td>
<td>1/30</td>
<td>12.94 (42.44)</td>
<td>0.94 (2,000)</td>
<td>0.07 (0.79)</td>
<td>0.30 (12.00)</td>
</tr>
<tr>
<td>Qr60</td>
<td>28.32 (60,000)</td>
<td>1/60</td>
<td>12.94 (42.44)</td>
<td>0.47 (1,000)</td>
<td>0.04 (0.39)</td>
<td>0.22 (8.49)</td>
</tr>
<tr>
<td>Qr120</td>
<td>28.32 (60,000)</td>
<td>1/120</td>
<td>12.94 (42.44)</td>
<td>0.24 (500)</td>
<td>0.02 (0.20)</td>
<td>0.15 (6.00)</td>
</tr>
</tbody>
</table>

7.2.5.4 Grid and time step sizes

Similar to the tunnel ventilated barn scenarios from section 6.2.6, a single pit-safety fan velocity of 12.94 m/s (42.44 ft/s) was selected for all cross-ventilated barn simulation cases. Since this was the maximum velocity in the computational domain, the final mesh with $144 \times 58 \times 26$ cells ($N_x \times N_y \times N_z$) and time step size of 0.25 seconds used for the tunnel ventilated simulations described in sections 6.2.6.8 and 6.2.6.9, respectively, were deemed suitable for the cross-ventilated simulations.
7.3 Results

The cross-ventilated barn simulation results are presented in this section. The procedures used to make barn measurement plane calculations and contamination maps described in section 6.3 were used to analyze simulation results. The term “contaminated” is used throughout to describe areas on the 0.15 m (6 in.) measurement plane in the barn where C(H₂S) ≥ 50 ppm. For this study, the barn airspace was considered to be contaminated when the concentration on the measurement plane became contaminated. This is because for gas to enter the barn airspace from the manure pit, it must pass through the measurement plane.

The criteria used to compare simulation cases with different pit-safety ventilation fan locations and flow rates were: percent area on the barn measurement plane where the H₂S concentration was 50 ppm or greater, the total duration of time when C(H₂S) was 50 ppm or greater, the maximum H₂S concentration in the barn overall and within each quintile, and the time required to reach 10 or 1 ppm anywhere inside the manure pit (Tₚₑₙ(10) and Tₚₑₙ(1), respectively).
7.3.1 Barn quintiles

The barn was divided into five 2.44 m (8 ft) wide quintiles for analysis (Figure 7.6). This was done to determine if the \( \text{H}_2\text{S} \) concentration in one or more quintiles never reached a level of 50 ppm for 10 minutes or more during manure pit-safety ventilation, then that quintile might be considered “safe” for occupation by animals if they could be corralled into that region of the barn. This might be achievable in barns with multiple pens where pen dividers could be used to exclude animals from regions where \( \text{H}_2\text{S} \) gas contamination was present. Division into quintiles also allows for finer quantitative comparisons than considering only the contaminated area of the entire barn. In addition to comparing the total barn area with a contaminant gas concentration \( \geq 50 \text{ ppm} \), it is possible to examine the area within each quintile with a contaminant gas concentration \( \geq 50 \text{ ppm} \) for each simulation case. One quintile contains 200 of the 1,000 total grid points on the barn measurement plane.

![Barn Exhaust Fan](Figure 7.6. Pit-safety fan locations and barn quintiles for cross-ventilated barn cases.)
7.3.2 Cross-ventilated barn simulation results

This section presents the CV barn simulation results for each simulation case. General discussion for all CV barn simulation cases follows in section 7.4.

All simulations started with the same initial conditions. At time $t = 0$, the barn airspace was full of atmospheric air (this included the open space in the porous media used to represent the slotted floor), and a uniform initial concentration of $H_2S$ gas filled the airspace inside the manure pit up to the bottom of the slotted floor. At time $t = 0^+$, the barn exhaust fans and manure pit-safety ventilation fan (used for all cases except the No Pit Fan case) were operating.

Cut plots for each simulation case illustrate the air flow pattern and gas concentration profile through the barn and manure pit during ventilation. Atmospheric air entered the barn through continuous eave inlet slots at the top of each barn side wall at the design velocity of 3.0 m/s (10.0 ft/s), then mixed with air inside the barn before being exhausted by the barn ventilation fans in the outlet side wall. In general, large counter-rotating recirculation regions were present in the airspace above the fully-slotted floor. The pit-safety ventilation fan (used for all simulations except the No Pit Fan case) forced fresh air into the manure pit, and some air flowed through the manure pit as a result of air movement created by the barn exhaust fans. The air flow in the manure pit airspace was relatively slow away from the pit-safety fan location, where the velocity was less than 0.4 m/s (1.3 ft/s) and large recirculation zones formed.

7.3.2.1 No pit fan

A simulation case with no pit-safety ventilation fan was used as a baseline for comparisons against other fan location and flow rates. In this configuration, the cross-ventilated barn exhaust fans were the only source of ventilation air flow. Since there was no pit-safety ventilation fan, $H_2S$ gas from the manure pit began to mix with the atmospheric air entering through the barn eave inlet slots. $H_2S$ gas exiting the manure pit was carried up into the barn.
airspace then removed from the barn by the exhaust fans at the outlet end of the barn. Figure 7.7 illustrates the air flow pattern through the barn and manure pit during ventilation. Figure 7.8 illustrates the air flow pattern across the barn and manure pit at the transverse centerline of the barn during ventilation. Figure 7.9 and Figure 7.10 show isometric views of 3D gas contours where C(H₂S) = 50 ppm in the barn airspace for the CV simulation case with no pit fan at times 30s, 60s, 120s, 180s, 300s, and 600s after the start of barn ventilation for initial manure pit H₂S concentrations of 100 ppm and 500 ppm.

Figure 7.7. Isometric view of CV barn showing streamlines at four cutting plane locations when time = 300s for the case with No Pit Fan.
Figure 7.8. Right cross section showing velocity vectors along the transverse centerline of the barn when time = 300s for the CV simulation case with no pit fan.
Figure 7.9. Isometric views of 3D gas contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace for the CV simulation case with no pit fan and initial manure pit $\text{H}_2\text{S}$ concentrations of (a) 100 ppm and (b) 500 ppm at times 30s, 60s, and 120s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace; $C(\text{H}_2\text{S}) > 50$ ppm beneath the red surfaces.
Figure 7.10. Isometric views of 3D gas contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace for the CV simulation case with no pit fan and initial manure pit $\text{H}_2\text{S}$ concentrations of (a) 100 ppm and (b) 500 ppm at times 180s, 300s, and 600s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace; $C(\text{H}_2\text{S}) > 50$ ppm beneath the red surfaces.
Figure 7.11 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn ventilation with initial manure pit H$_2$S concentrations equal to 100, 200, 300, 400, and 500 ppm for the case with no pit-safety ventilation fan. Table 7.4 lists comparison statistics for the simulation case with no pit-safety ventilation fan for several initial manure pit concentration values. The statistics include the percentage of contaminated area where C(H$_2$S) $\geq$ 50 ppm, duration of time when C(H$_2$S) $\geq$ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of time required to reach a maximum H$_2$S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.

Figure 7.11. Plot showing contaminated areas on the CV barn measurement plane during barn ventilation for the case with no pit fan.
Table 7.4. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn ventilation for the No Pit Fan CV case with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>10 %</td>
<td>70 s</td>
</tr>
<tr>
<td></td>
<td>70 s&lt;sup&gt;b&lt;/sup&gt;</td>
<td>17 ppm</td>
<td>22 ppm</td>
<td>47 ppm</td>
<td>47 ppm</td>
<td>50 ppm</td>
<td>1,176 s&lt;sup&gt;d&lt;/sup&gt;</td>
<td>2,141 s&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>55</td>
<td>11 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1 %</td>
<td>81 %</td>
<td>130 s</td>
</tr>
<tr>
<td></td>
<td>138 s</td>
<td>17 ppm</td>
<td>23 ppm</td>
<td>48 ppm</td>
<td>51 ppm</td>
<td>51 ppm</td>
<td>1,180 s</td>
<td>2,147 s</td>
</tr>
<tr>
<td>75</td>
<td>25 %</td>
<td>41 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1 %</td>
<td>81 %</td>
<td>55 ppm</td>
<td>55 ppm</td>
</tr>
<tr>
<td></td>
<td>196 s</td>
<td>18 ppm</td>
<td>25 ppm</td>
<td>51 ppm</td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>1,195 s</td>
<td>2,171 s</td>
</tr>
<tr>
<td>100</td>
<td>49 %</td>
<td>88 %</td>
<td>0 %</td>
<td>0 %</td>
<td>55 %</td>
<td>100 %</td>
<td>1,516 s</td>
<td>2,353 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>33 ppm</td>
<td>45 ppm</td>
<td>94 ppm</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>1,516 s</td>
<td>2,353 s</td>
</tr>
<tr>
<td>200</td>
<td>61 %</td>
<td>100 %</td>
<td>14 %</td>
<td>3 %</td>
<td>90 %</td>
<td>100 %</td>
<td>1,821 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>17 s</td>
<td>110 s</td>
<td>288 s</td>
<td>293 s</td>
<td>207 s</td>
<td>1,821 s</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>66 %</td>
<td>100 %</td>
<td>25 %</td>
<td>6 %</td>
<td>100 %</td>
<td>100 %</td>
<td>1,968 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>37 s</td>
<td>200 s</td>
<td>288 s</td>
<td>294 s</td>
<td>294 s</td>
<td>1,968 s</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>78 %</td>
<td>100 %</td>
<td>49 %</td>
<td>40 %</td>
<td>100 %</td>
<td>100 %</td>
<td>2,079 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>129 s</td>
<td>275 s</td>
<td>288 s</td>
<td>295 s</td>
<td>295 s</td>
<td>2,079 s</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>92 %</td>
<td>100 %</td>
<td>77 %</td>
<td>85 %</td>
<td>100 %</td>
<td>100 %</td>
<td>2,141 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>159 s</td>
<td>275 s</td>
<td>290 s</td>
<td>295 s</td>
<td>295 s</td>
<td>2,141 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>167 ppm</td>
<td>224 ppm</td>
<td>468 ppm</td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>2,141 s</td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration $\geq 50$ ppm during the first 300 s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration $\geq 50$ ppm during the first 300 s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300 s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
The following observations were made for the simulation case with no pit fan:

1. Quintile I was never completely clear, even when \( C_0 = 50 \) ppm. Quintile I was 10\% contaminated when \( C_0 = 50 \) ppm and 100\% contaminated when \( C_0 \geq 75 \) ppm.

2. Quintile II was only 1\% contaminated when \( C_0 = 55 \) ppm and 100\% contaminated when \( C_0 \geq 300 \) ppm.

3. Quintile III was not contaminated when \( C_0 \leq 100 \) ppm. Quintile III was only 3\% contaminated when \( C_0 = 200 \) ppm, and was 85\% contaminated when \( C_0 = 500 \) ppm.

4. Quintile IV was not contaminated when \( C_0 \leq 100 \) ppm. Quintile III was only 14\% contaminated when \( C_0 = 200 \) ppm, and was 77\% contaminated when \( C_0 = 500 \) ppm.

5. Quintile V was 100\% contaminated with \( C(H_2S) \geq 50 \) ppm when \( C_0 \geq 200 \) ppm inside the manure pit, and was 3\% contaminated when \( C_0 = 51 \) ppm.
7.3.2.2 CV11

Simulation cases for pit-safety fan location (1,1) were performed using $Q_{\text{ratio}}$ of 30, 60, and 120. Figure 7.12 illustrates the air flow pattern across the barn and manure pit at the centerline of the pit-safety ventilation fan at location (1,1) for $Q_{r30}$. Figure 7.13 and Figure 7.14 show isometric views of 3D gas contours where $C(H_2S) = 50$ ppm in the barn airspace for CV simulation case location (1,1) and $Q_{r30}$ at times 30s, 60s, 120s, 180s, 300s, and 600s after the start of pit and barn ventilation for initial manure pit $H_2S$ concentrations of 100 ppm and 500 ppm.

Figure 7.12. Right cross section showing velocity vectors at the centerline of the pit-safety ventilation fan at CV simulation case location (1,1) and $Q_{r30}$ when time = 300s.
Figure 7.13. Isometric views of 3D gas contours where \( \text{C(H}_2\text{S)} = 50 \text{ ppm} \) in the barn airspace for CV simulation case CV11Qr30 and initial manure pit \( \text{H}_2\text{S} \) concentrations of (a) 100 ppm and (b) 500 ppm at times 30s, 60s, and 120s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where \( \text{C(H}_2\text{S)} = 50 \text{ ppm} \) in the barn airspace; \( \text{C(H}_2\text{S)} > 50 \text{ ppm} \) beneath the red surfaces.
Figure 7.14. Isometric views of 3D gas contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace for CV simulation case CV11Qr30 and initial manure pit $\text{H}_2\text{S}$ concentrations of (a) 100 ppm and (b) 500 ppm at times 180s, 300s, and 600s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace; $C(\text{H}_2\text{S}) > 50$ ppm beneath the red surfaces.
Figure 7.15 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation with initial manure pit H₂S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (1,1) and Q\textsubscript{ratios} 30, 60, and 120. Table 7.5, Table 7.6, and Table 7.7 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (1,1) and Q\textsubscript{ratios} 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H₂S) ≥ 50 ppm, duration of time when C(H₂S) ≥ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H₂S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.
Figure 7.15. Plot showing contaminated areas on the CV barn measurement plane during barn and pit-safety ventilation for case CV11.
Table 7.5. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV11Qr30 with Tpel values.

<table>
<thead>
<tr>
<th>Co (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>Tpel(10)</th>
<th>Tpel(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>17%</td>
<td>759 s&lt;sup&gt;d&lt;/sup&gt;</td>
<td>1,136 s&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>110 s&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>110 s</td>
<td>50 ppm</td>
<td>50 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm&lt;sup&gt;c&lt;/sup&gt;</td>
<td>49 ppm</td>
<td>32 ppm</td>
<td>24 ppm</td>
<td>49 ppm</td>
<td>50 ppm</td>
<td>51 ppm</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>12%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
<td>57%</td>
<td>761 s</td>
<td>1,138 s</td>
</tr>
<tr>
<td></td>
<td>156 s</td>
<td>8 s</td>
<td>0 s</td>
<td>0 s</td>
<td>10 s</td>
<td>150 s</td>
<td>51 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>50 ppm</td>
<td>32 ppm</td>
<td>25 ppm</td>
<td>50 ppm</td>
<td>51 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>27%</td>
<td>31%</td>
<td>0%</td>
<td>0%</td>
<td>6%</td>
<td>99%</td>
<td>770 s</td>
<td>1,154 s</td>
</tr>
<tr>
<td></td>
<td>289 s</td>
<td>39 s</td>
<td>0 s</td>
<td>0 s</td>
<td>120 s</td>
<td>265 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>54 ppm</td>
<td>35 ppm</td>
<td>27 ppm</td>
<td>54 ppm</td>
<td>55 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>44%</td>
<td>69%</td>
<td>0%</td>
<td>0%</td>
<td>49%</td>
<td>100%</td>
<td>802 s</td>
<td>1,168 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>60 s</td>
<td>0 s</td>
<td>0 s</td>
<td>212 s</td>
<td>290 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>74 ppm</td>
<td>47 ppm</td>
<td>36 ppm</td>
<td>74 ppm</td>
<td>75 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>53%</td>
<td>90%</td>
<td>1%</td>
<td>0%</td>
<td>75%</td>
<td>100%</td>
<td>874 s</td>
<td>1,176 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>80 s</td>
<td>4 s</td>
<td>0 s</td>
<td>234 s</td>
<td>291 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>98 ppm</td>
<td>63 ppm</td>
<td>49 ppm</td>
<td>98 ppm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>68%</td>
<td>97%</td>
<td>31%</td>
<td>10%</td>
<td>100%</td>
<td>100%</td>
<td>990 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>140 s</td>
<td>25 s</td>
<td>131 s</td>
<td>288 s</td>
<td>293 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>196 ppm</td>
<td>127 ppm</td>
<td>97 ppm</td>
<td>196 ppm</td>
<td>200 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>81%</td>
<td>100%</td>
<td>59%</td>
<td>46%</td>
<td>100%</td>
<td>100%</td>
<td>1,028 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>170 s</td>
<td>150 s</td>
<td>290 s</td>
<td>288 s</td>
<td>294 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>295 ppm</td>
<td>190 ppm</td>
<td>146 ppm</td>
<td>295 ppm</td>
<td>300 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>96%</td>
<td>100%</td>
<td>85%</td>
<td>94%</td>
<td>100%</td>
<td>100%</td>
<td>1,107 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>250 s</td>
<td>190 s</td>
<td>291 s</td>
<td>290 s</td>
<td>294 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>393 ppm</td>
<td>253 ppm</td>
<td>195 ppm</td>
<td>393 ppm</td>
<td>400 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>98%</td>
<td>100%</td>
<td>91%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>1,136 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>290 s</td>
<td>230 s</td>
<td>291 s</td>
<td>290 s</td>
<td>295 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>491 ppm</td>
<td>316 ppm</td>
<td>243 ppm</td>
<td>491 ppm</td>
<td>500 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H2S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H2S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H2S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H2S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H2S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before Tpel was reached.
Table 7.6. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV11Qr60 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>4 %$^a$</td>
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<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>18 % 100 s</td>
<td>50 ppm</td>
</tr>
<tr>
<td></td>
<td>100 s$^b$</td>
<td>0 s</td>
<td>0 s</td>
<td>22 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>56 % 150 s</td>
<td>51 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>49 ppm</td>
<td>20 ppm</td>
<td>48 ppm</td>
<td>48 ppm</td>
<td>871 s$^d$</td>
<td>1,157 s$^e$</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>11 %</td>
<td>1 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>56 % 150 s</td>
<td>51 ppm</td>
</tr>
<tr>
<td></td>
<td>158 s</td>
<td>8 s</td>
<td>0 s</td>
<td>22 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>874 s 1,161 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>50 ppm</td>
<td>21 ppm</td>
<td>49 ppm</td>
<td>49 ppm</td>
<td>883 s 1,175 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>25 %</td>
<td>33 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1 %</td>
<td>91 %</td>
<td>871 s 1,157 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>198 s</td>
<td>38 s</td>
<td>0 s</td>
<td>24 ppm</td>
<td>0 s</td>
<td>0 s</td>
<td>871 s 1,157 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>54 ppm</td>
<td>22 ppm</td>
<td>52 ppm</td>
<td>52 ppm</td>
<td>883 s 1,175 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>41 %</td>
<td>72 %</td>
<td>0 %</td>
<td>0 %</td>
<td>35 %</td>
<td>100 %</td>
<td>932 s 1,239 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>70 s</td>
<td>0 s</td>
<td>150 s</td>
<td>0 s</td>
<td>0 s</td>
<td>932 s 1,239 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>74 ppm</td>
<td>30 ppm</td>
<td>71 ppm</td>
<td>71 ppm</td>
<td>932 s 1,239 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>51 %</td>
<td>93 %</td>
<td>0 %</td>
<td>0 %</td>
<td>62 %</td>
<td>100 %</td>
<td>974 s 1,295 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>80 s</td>
<td>0 s</td>
<td>224 s</td>
<td>0 s</td>
<td>0 s</td>
<td>974 s 1,295 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>98 ppm</td>
<td>40 ppm</td>
<td>224 s</td>
<td>0 s</td>
<td>0 s</td>
<td>974 s 1,295 s</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>64 %</td>
<td>100 %</td>
<td>17 %</td>
<td>6 %</td>
<td>97 %</td>
<td>100 %</td>
<td>1,049 s -</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>130 s</td>
<td>22 s</td>
<td>110 s</td>
<td>288 s</td>
<td>288 s</td>
<td>1,049 s -</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>197 ppm</td>
<td>81 ppm</td>
<td>191 ppm</td>
<td>191 ppm</td>
<td>288 s 288 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>73 %</td>
<td>100 %</td>
<td>40 %</td>
<td>24 %</td>
<td>100 %</td>
<td>100 %</td>
<td>1,097 s -</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>150 s</td>
<td>109 s</td>
<td>165 s</td>
<td>165 s</td>
<td>288 s 294 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>295 ppm</td>
<td>121 ppm</td>
<td>131 ppm</td>
<td>131 ppm</td>
<td>288 s 294 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>91 %</td>
<td>100 %</td>
<td>77 %</td>
<td>76 %</td>
<td>100 %</td>
<td>100 %</td>
<td>1,131 s -</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>200 s</td>
<td>170 s</td>
<td>275 s</td>
<td>275 s</td>
<td>290 s 294 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>393 ppm</td>
<td>161 ppm</td>
<td>381 ppm</td>
<td>381 ppm</td>
<td>290 s 294 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>97 %</td>
<td>100 %</td>
<td>87 %</td>
<td>99 %</td>
<td>100 %</td>
<td>100 %</td>
<td>1,157 s -</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>250 s</td>
<td>190 s</td>
<td>280 s</td>
<td>280 s</td>
<td>295 s 295 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>492 ppm</td>
<td>201 ppm</td>
<td>476 ppm</td>
<td>476 ppm</td>
<td>295 s 295 s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.

b. Duration of time with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.

c. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.

d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.

e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 7.7. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV11Qr120 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>Barn Quintile (For first 300s)</th>
<th></th>
<th>$T_{pel}$ (10)</th>
<th>$T_{pel}$ (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2 %$^a$</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td></td>
<td>70 s$^b$</td>
<td>49 ppm</td>
<td>21 ppm</td>
<td>22 ppm</td>
<td>47 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>12 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>148 s</td>
<td>8 s</td>
<td>22 ppm</td>
<td>48 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>51 ppm</td>
<td>50 ppm</td>
<td>22 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>24 %</td>
<td>37 %</td>
<td>0 %</td>
<td>1 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>188 s</td>
<td>38 s</td>
<td>24 ppm</td>
<td>52 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>55 ppm</td>
<td>54 ppm</td>
<td>24 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>41 %</td>
<td>72 %</td>
<td>0 %</td>
<td>31 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 s</td>
<td>60 s</td>
<td>0 %</td>
<td>160 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75 ppm</td>
<td>74 ppm</td>
<td>32 ppm</td>
<td>71 ppm</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>50 %</td>
<td>92 %</td>
<td>0 %</td>
<td>57 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 s</td>
<td>80 s</td>
<td>0 %</td>
<td>264 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 ppm</td>
<td>98 ppm</td>
<td>43 ppm</td>
<td>95 ppm</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>62 %</td>
<td>100 %</td>
<td>16 %</td>
<td>91 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 s</td>
<td>120 s</td>
<td>21 s</td>
<td>288 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 ppm</td>
<td>197 ppm</td>
<td>86 ppm</td>
<td>190 ppm</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>68 %</td>
<td>100 %</td>
<td>27 %</td>
<td>12 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 s</td>
<td>160 s</td>
<td>49 s</td>
<td>160 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 ppm</td>
<td>295 ppm</td>
<td>128 ppm</td>
<td>132 ppm</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>83 %</td>
<td>100 %</td>
<td>60 %</td>
<td>57 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 s</td>
<td>200 s</td>
<td>139 s</td>
<td>275 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>400 ppm</td>
<td>393 ppm</td>
<td>171 ppm</td>
<td>176 ppm</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>94 %</td>
<td>100 %</td>
<td>79 %</td>
<td>91 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 s</td>
<td>230 s</td>
<td>170 s</td>
<td>275 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 ppm</td>
<td>492 ppm</td>
<td>214 ppm</td>
<td>475 ppm</td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
The following observations were made for simulation case CV11:

1. Quintile I was never completely clear for all three $Q_{ratios}$, even when $C_0 = 50$ ppm, and was 100% contaminated for all three $Q_{ratios}$ when $C_0 \geq 75$ ppm.

2. Quintile II was 1% contaminated when $C_0 = 51$ ppm for $Q_{r30}$, and when $C_0 = 55$ ppm for $Q_{r60}$ and $Q_{r120}$. Quintile II was 100% contaminated when $C_0 \geq 200$ ppm for $Q_{r30}$, and when $C_0 \geq 300$ ppm for $Q_{r60}$ and $Q_{r120}$.

3. Quintile III was not contaminated when $C_0 \leq 100$ ppm for all three $Q_{ratios}$, and was 100% contaminated when $C_0 = 500$ ppm for $Q_{r30}$. Quintile III was 99% and 91% contaminated when $C_0 = 500$ ppm for $Q_{r60}$ and $Q_{r120}$, respectively.

4. Quintile IV was only 1% contaminated when $C_0 = 100$ ppm for $Q_{r30}$, but was not contaminated when $C_0 = 100$ ppm for $Q_{r60}$ and $Q_{r120}$. Quintile IV was 91%, 87%, and 79% contaminated when $C_0 = 500$ ppm for $Q_{r30}$, 60, and 120, respectively.

5. For all three $Q_{ratios}$, Quintile V was 1% contaminated when $C_0 = 55$ ppm inside the manure pit, and was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 300$ ppm inside the manure pit.
7.3.2.3 CV13

Simulation cases for pit-safety fan location (1,3) were performed using $Q_{\text{ratio}}$ of 30, 60, and 120. Figure 7.16 illustrates the air flow pattern across the barn and manure pit at the centerline of the pit-safety ventilation fan at location (1,3) for $Qr30$. Figure 7.17 and Figure 7.18 show isometric views of 3D gas contours where $C(H_2S) = 50$ ppm in the barn airspace for CV simulation case location (1,3) and $Qr30$ at times 30s, 60s, 120s, 180s, 300s, and 600s after the start of pit and barn ventilation for initial manure pit $H_2S$ concentrations of 100 ppm and 500 ppm.

Figure 7.16. Right cross section showing velocity vectors at the centerline of the pit-safety ventilation fan at CV simulation case location (1,3) and $Qr30$ when time = 300s.
Figure 7.17. Isometric views of 3D gas contours where C(H$_2$S) = 50 ppm in the barn airspace for CV simulation case CV13Qr30 and initial manure pit H$_2$S concentrations of (a) 100 ppm and (b) 500 ppm at times 30s, 60s, and 120s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where C(H$_2$S) = 50 ppm in the barn airspace; C(H$_2$S) > 50 ppm beneath the red surfaces.
Figure 7.18. Isometric views of 3D gas contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace for CV simulation case CV13Qr30 and initial manure pit $\text{H}_2\text{S}$ concentrations of (a) 100 ppm and (b) 500 ppm at times 180s, 300s, and 600s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace; $C(\text{H}_2\text{S}) > 50$ ppm beneath the red surfaces.
Figure 7.19 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation with initial manure pit H₂S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (1,3) and Qᵣatios 30, 60, and 120. Table 7.8, Table 7.9, and Table 7.10 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (1,3) and Qᵣatios 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H₂S) ≥ 50 ppm, duration of time when C(H₂S) ≥ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H₂S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.
Figure 7.19. Plot showing contaminated areas on the CV barn measurement plane during barn and pit-safety ventilation for case CV13.
Table 7.8. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV13Qr30 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>4 %$^a$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20%</td>
<td>702 s$^d$</td>
</tr>
<tr>
<td></td>
<td>110 s$^b$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>110 s</td>
<td>1,029 s$^e$</td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>0</td>
<td>26 ppm</td>
<td>25 ppm</td>
<td>49 ppm</td>
<td>50 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>9 %</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>41%</td>
<td>704 s</td>
</tr>
<tr>
<td></td>
<td>165 s</td>
<td>15 s</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>160 s</td>
<td>1,037 s</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>50 ppm</td>
<td>26 ppm</td>
<td>25 ppm</td>
<td>50 ppm</td>
<td>51 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>22 %</td>
<td>42</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>64%</td>
<td>714 s</td>
</tr>
<tr>
<td></td>
<td>297 s</td>
<td>37 s</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>135 s</td>
<td>270 s</td>
<td>1,053 s</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>54 ppm</td>
<td>28 ppm</td>
<td>27 ppm</td>
<td>54 ppm</td>
<td>55 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>41 %</td>
<td>77</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>42%</td>
<td>86%</td>
<td>763 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>60 s</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>224 s</td>
<td>294 s</td>
<td>1,116 s</td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>74 ppm</td>
<td>39 ppm</td>
<td>37 ppm</td>
<td>73 ppm</td>
<td>75 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>49 %</td>
<td>95</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>60%</td>
<td>88%</td>
<td>784 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>90 s</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>256 s</td>
<td>296 s</td>
<td>1,135 s</td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>99 ppm</td>
<td>51 ppm</td>
<td>50 ppm</td>
<td>98 ppm</td>
<td>100 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>62 %</td>
<td>100%</td>
<td>17%</td>
<td>7</td>
<td>93%</td>
<td>95%</td>
<td>95%</td>
<td>898 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>130 s</td>
<td>25 s</td>
<td>100 s</td>
<td>289 s</td>
<td>298 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>197 ppm</td>
<td>103 ppm</td>
<td>100 ppm</td>
<td>196 ppm</td>
<td>200 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>70 %</td>
<td>100%</td>
<td>36%</td>
<td>23%</td>
<td>96%</td>
<td>98%</td>
<td>98%</td>
<td>972 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>190 s</td>
<td>119 s</td>
<td>262 s</td>
<td>300 s</td>
<td>300 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>296 ppm</td>
<td>154 ppm</td>
<td>150 ppm</td>
<td>294 ppm</td>
<td>300 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>88 %</td>
<td>100%</td>
<td>68%</td>
<td>73%</td>
<td>98%</td>
<td>100%</td>
<td>100%</td>
<td>992 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>230 s</td>
<td>189 s</td>
<td>286 s</td>
<td>300 s</td>
<td>300 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>394 ppm</td>
<td>206 ppm</td>
<td>200 ppm</td>
<td>392 ppm</td>
<td>400 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>91 %</td>
<td>100%</td>
<td>77%</td>
<td>81%</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
<td>1,029 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>260 s</td>
<td>239 s</td>
<td>288 s</td>
<td>300 s</td>
<td>300 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>493 ppm</td>
<td>257 ppm</td>
<td>249 ppm</td>
<td>490 ppm</td>
<td>500 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Percent of area with $H_2S$ concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
- Duration of time with $H_2S$ concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
- Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
- Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of $10$ ppm.
- Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of $1$ ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 7.9. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV13Qr60 with T<sub>pel</sub> values.

<table>
<thead>
<tr>
<th>C&lt;sub&gt;0&lt;/sub&gt; (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>T&lt;sub&gt;pel(10)&lt;/sub&gt;</th>
<th>T&lt;sub&gt;pel(1)&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3 %&lt;sup&gt;a&lt;/sup&gt; 90 s&lt;sup&gt;b&lt;/sup&gt; 50 ppm&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6 % 148 s 51 ppm</td>
<td>22 % 207 s 55 ppm</td>
<td>40 % 74 ppm</td>
<td>49 % 98 ppm</td>
<td>75 ppm 300 s</td>
<td>677 s&lt;sup&gt;4&lt;/sup&gt; 679 s&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 % 0 s 49 ppm</td>
<td>0 % 0 s 21 ppm</td>
<td>42 % 0 s 23 ppm</td>
<td>0 % 0 s 35 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>74 ppm 75 ppm</td>
<td>1,025 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 % 0 s 21 ppm</td>
<td>0 % 0 s 24 ppm</td>
<td>0 % 0 s 49 ppm</td>
<td>0 % 0 s 53 ppm</td>
<td>0 % 0 s 59 ppm</td>
<td>75 ppm 75 ppm</td>
<td>1,064 s</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>3 % 140 s 51 ppm</td>
<td>22 % 207 s 55 ppm</td>
<td>40 % 74 ppm</td>
<td>49 % 98 ppm</td>
<td>75 ppm 300 s</td>
<td>679 s&lt;sup&gt;e&lt;/sup&gt; 971 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 % 0 s 21 ppm</td>
<td>0 % 0 s 24 ppm</td>
<td>0 % 0 s 49 ppm</td>
<td>0 % 0 s 53 ppm</td>
<td>0 % 0 s 59 ppm</td>
<td>75 ppm 75 ppm</td>
<td>1,025 s</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>3 % 173 s 50 ppm</td>
<td>22 % 207 s 55 ppm</td>
<td>40 % 74 ppm</td>
<td>49 % 98 ppm</td>
<td>75 ppm 300 s</td>
<td>686 s&lt;sup&gt;e&lt;/sup&gt; 982 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 % 0 s 21 ppm</td>
<td>0 % 0 s 24 ppm</td>
<td>0 % 0 s 49 ppm</td>
<td>0 % 0 s 53 ppm</td>
<td>0 % 0 s 59 ppm</td>
<td>75 ppm 75 ppm</td>
<td>1,064 s</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>63 % 300 s 75 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>724 s&lt;sup&gt;e&lt;/sup&gt; 1,025 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 % 140 s 51 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 % 23 s 82 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>63 % 300 s 75 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>757 s&lt;sup&gt;e&lt;/sup&gt; 1,064 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 % 140 s 51 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 % 23 s 82 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>63 % 300 s 75 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>835 s&lt;sup&gt;e&lt;/sup&gt; -</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 % 140 s 51 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 % 23 s 82 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>63 % 300 s 75 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>895 s&lt;sup&gt;e&lt;/sup&gt; -</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 % 140 s 51 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 % 23 s 82 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>63 % 300 s 75 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>938 s&lt;sup&gt;e&lt;/sup&gt; -</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 % 140 s 51 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 % 23 s 82 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>63 % 300 s 75 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>63 % 300 s 100 ppm</td>
<td>969 s&lt;sup&gt;e&lt;/sup&gt; -</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 % 140 s 51 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>90 % 98 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 % 23 s 82 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>0 % 0 s 46 ppm</td>
<td>296 s 296 s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H<sub>2</sub>S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H<sub>2</sub>S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H<sub>2</sub>S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H<sub>2</sub>S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H<sub>2</sub>S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before T<sub>pel</sub> was reached.
Table 7.10. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV13Qr120 with T_{pel} values.

<table>
<thead>
<tr>
<th>C_0 (ppm)</th>
<th>Overall</th>
<th>Barn Quintile (For first 300s)</th>
<th>T_{pel(10)}</th>
<th>T_{pel(1)}</th>
</tr>
</thead>
</table>
| 50        | 2 %  
70 s  
50 ppm  | 0 %  
0 s  
49 ppm  | 0 %  
0 s  
18 ppm  | 0 %  
0 s  
23 ppm  | 0 %  
0 s  
48 ppm  | 10 %  
70 s  
50 ppm  | 979 s  
1,314 s  |
| 51        | 8 %  
138 s  
51 ppm  | 2 %  
8 s  
50 ppm  | 0 %  
0 s  
18 ppm  | 0 %  
0 s  
23 ppm  | 0 %  
0 s  
49 ppm  | 38 %  
140 s  
51 ppm  | 983 s  
1,315 s  |
| 55        | 21 %  
187 s  
55 ppm  | 42 %  
74 s  
54 ppm  | 0 %  
0 s  
20 ppm  | 0 %  
0 s  
25 ppm  | 2 %  
70 s  
52 ppm  | 63 %  
160 s  
55 ppm  | 1,005 s  
1,319 s  |
| 75        | 39 %  
270 s  
75 ppm  | 74 %  
70 s  
74 ppm  | 0 %  
0 s  
18 ppm  | 0 %  
0 s  
23 ppm  | 29 %  
160 s  
71 ppm  | 92 %  
261 s  
75 ppm  | 1,058 s  
1,337 s  |
| 100       | 49 %  
300 s  
100 ppm | 91 %  
80 s  
98 ppm  | 0 %  
0 s  
36 ppm  | 0 %  
0 s  
45 ppm  | 55 %  
224 s  
95 ppm  | 98 %  
292 s  
100 ppm | 1,078 s  
1,374 s  |
| 200       | 62 %  
300 s  
200 ppm | 100 %  
140 s  
197 ppm | 15 %  
22 s  
73 ppm  | 3 %  
130 s  
91 ppm  | 94 %  
288 s  
190 ppm | 100 %  
288 s  
200 ppm | 1,159 s  -  |
| 300       | 68 %  
300 s  
300 ppm | 100 %  
160 s  
295 ppm | 27 %  
69 s  
109 ppm | 13 %  
185 s  
136 ppm | 100 %  
288 s  
285 ppm | 100 %  
295 s  
300 ppm | 1,218 s  -  |
| 400       | 82 %  
300 s  
400 ppm | 100 %  
210 s  
394 ppm | 57 %  
139 s  
145 ppm | 51 %  
280 s  
181 ppm | 100 %  
290 s  
381 ppm | 100 %  
295 s  
400 ppm | 1,288 s  -  |
| 500       | 89 %  
300 s  
500 ppm | 100 %  
250 s  
492 ppm | 70 %  
189 s  
181 ppm | 77 %  
280 s  
226 ppm | 100 %  
290 s  
476 ppm | 100 %  
297 s  
500 ppm | 1,314 s  -  |

a. Percent of area with H_2S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H_2S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H_2S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H_2S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H_2S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before T_{pel} was reached.
The following were observed for simulation case CV13:

1. Quintile I was never completely clear for all three $Q_{r\text{tios}}$, even when $C_0 = 50$ ppm. Quintile I was 100% contaminated when $C_0 \geq 400$ ppm for Qr30, and was 100% contaminated when $C_0 \geq 300$ ppm for Qr60 and 120.

2. Quintile II was not contaminated when $C_0 \leq 55$ ppm for all three $Q_{r\text{tios}}$. Quintile II was 99% contaminated when $C_0 = 500$ ppm for Qr30. Quintile II was 100% contaminated when $C_0 \geq 400$ ppm for Qr60 and when $C_0 \geq 300$ ppm for Qr120.

3. Quintile III was not contaminated when $C_0 \leq 100$ ppm for all three $Q_{r\text{tios}}$. Quintile III was 81%, 80%, and 77% contaminated when $C_0 = 500$ ppm for Qr30, 60, and 120, respectively.

4. Quintile IV was only 1% contaminated when $C_0 = 100$ ppm for Qr30, but was not contaminated when $C_0 = 100$ ppm for Qr60 and 120. Quintile IV was 77%, 74%, and 70% contaminated when $C_0 = 500$ ppm for Qr30, 60, and 120, respectively.

5. Quintile V was only 5%, 2%, and 2% contaminated when $C_0 = 51$ ppm inside the manure pit for Qr30, 60, and 120, respectively. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 200$ ppm inside the manure pit for all three $Q_{r\text{tios}}$.  

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7.3.2.4 CV21

Simulation cases for pit-safety fan location (2,1) were performed using $Q_{\text{ratio}}$ of 30, 60, and 120. Figure 7.20 illustrates the air flow pattern across the barn and manure pit at the centerline of the pit-safety ventilation fan at location (2,1) for $Q_{r30}$. Figure 7.21 and Figure 7.22 show isometric views of 3D gas contours where $C(H_2S) = 50$ ppm in the barn airspace for CV simulation case location (2,1) and $Q_{r30}$ at times 30s, 60s, 120s, 180s, 300s, and 600s after the start of pit and barn ventilation for initial manure pit $H_2S$ concentrations of 100 ppm and 500 ppm.

Figure 7.20. Right cross section showing velocity vectors at the centerline of the pit-safety ventilation fan at CV simulation case location (2,1) and $Q_{r30}$ when time = 300s.
Figure 7.21. Isometric views of 3D gas contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace for CV simulation case CV21Qr30 and initial manure pit $\text{H}_2\text{S}$ concentrations of (a) 100 ppm and (b) 500 ppm at times 30s, 60s, and 120s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace; $C(\text{H}_2\text{S}) > 50$ ppm beneath the red surfaces.
Figure 7.22. Isometric views of 3D gas contours where C(H₂S) = 50 ppm in the barn airspace for CV simulation case CV21Qr30 and initial manure pit H₂S concentrations of (a) 100 ppm and (b) 500 ppm at times 180s, 300s, and 600s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where C(H₂S) = 50 ppm in the barn airspace; C(H₂S) > 50 ppm beneath the red surfaces.
Figure 7.23 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation with initial manure pit H$_2$S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (2,1) and Q$_{ratios}$ 30, 60, and 120. Table 7.11, Table 7.12, and Table 7.13 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (2,1) and Q$_{ratios}$ 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H$_2$S) $\geq$ 50 ppm, duration of time when C(H$_2$S) $\geq$ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H$_2$S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.
Figure 7.23. Plot showing contaminated areas on the CV barn measurement plane during barn and pit-safety ventilation for case CV21.
Table 7.11. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV21Qr30 with T_{pel} values.

<table>
<thead>
<tr>
<th>C_0 (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>T_{pel(10)}</th>
<th>T_{pel(1)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>15 %</td>
<td>493 s</td>
<td>816 s</td>
</tr>
<tr>
<td></td>
<td>70 s b</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>15 %</td>
<td>70 s</td>
<td>50 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm c</td>
<td>49 ppm</td>
<td>20 ppm</td>
<td>25 ppm</td>
<td>49 ppm</td>
<td>50 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>16 %</td>
<td>5 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1 %</td>
<td>72 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 s</td>
<td>10 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>20 s</td>
<td>90 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>50 ppm</td>
<td>20 ppm</td>
<td>25 ppm</td>
<td>50 ppm</td>
<td>51 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>28 %</td>
<td>36 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>7 %</td>
<td>99 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>138 s</td>
<td>28 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>100 s</td>
<td>110 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>54 ppm</td>
<td>22 ppm</td>
<td>27 ppm</td>
<td>54 ppm</td>
<td>55 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>44 %</td>
<td>72 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>47 %</td>
<td>100 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>210 s</td>
<td>60 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>120 s</td>
<td>198 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>74 ppm</td>
<td>30 ppm</td>
<td>37 ppm</td>
<td>74 ppm</td>
<td>75 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>52 %</td>
<td>91 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>70 %</td>
<td>100 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>230 s</td>
<td>80 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>184 s</td>
<td>221 s</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>98 ppm</td>
<td>40 ppm</td>
<td>49 ppm</td>
<td>99 ppm</td>
<td>100 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>69 %</td>
<td>100 %</td>
<td>30 %</td>
<td>16 %</td>
<td>98 %</td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>120 s</td>
<td>30 s</td>
<td>240 s</td>
<td>288 s</td>
<td>293 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>197 ppm</td>
<td>79 ppm</td>
<td>99 ppm</td>
<td>197 ppm</td>
<td>200 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>85 %</td>
<td>100 %</td>
<td>68 %</td>
<td>58 %</td>
<td>100 %</td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>150 s</td>
<td>130 s</td>
<td>275 s</td>
<td>288 s</td>
<td>294 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>295 ppm</td>
<td>119 ppm</td>
<td>148 ppm</td>
<td>296 ppm</td>
<td>300 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>97 %</td>
<td>100 %</td>
<td>88 %</td>
<td>95 %</td>
<td>100 %</td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>190 s</td>
<td>180 s</td>
<td>275 s</td>
<td>288 s</td>
<td>294 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>394 ppm</td>
<td>159 ppm</td>
<td>198 ppm</td>
<td>394 ppm</td>
<td>400 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>99 %</td>
<td>100 %</td>
<td>94 %</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>230 s</td>
<td>260 s</td>
<td>282 s</td>
<td>290 s</td>
<td>295 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>492 ppm</td>
<td>198 ppm</td>
<td>247 ppm</td>
<td>493 ppm</td>
<td>500 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before T_{pel} was reached.
Table 7.12. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV21Qr60 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel(10)}$</th>
<th>$T_{pel(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5 %&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>27 %</td>
<td>412 s&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>110 s</td>
<td>19 ppm</td>
<td>19 ppm</td>
<td>19 ppm</td>
<td>19 ppm</td>
<td>19 ppm</td>
<td>19 ppm</td>
<td>19 ppm</td>
</tr>
<tr>
<td>51</td>
<td>14 %</td>
<td>2 %</td>
<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
<td>2 %</td>
<td>67 %</td>
<td>414 s</td>
</tr>
<tr>
<td></td>
<td>138 s</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
</tr>
<tr>
<td>55</td>
<td>26 %</td>
<td>37 %</td>
<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
<td>2 %</td>
<td>92 %</td>
<td>423 s</td>
</tr>
<tr>
<td></td>
<td>198 s</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
</tr>
<tr>
<td>75</td>
<td>42 %</td>
<td>75 %</td>
<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
<td>2 %</td>
<td>100 %</td>
<td>465 s</td>
</tr>
<tr>
<td></td>
<td>250 s</td>
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<tr>
<td>100</td>
<td>50 %</td>
<td>94 %</td>
<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
<td>2 %</td>
<td>100 %</td>
<td>500 s</td>
</tr>
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<td>290 s</td>
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</tr>
<tr>
<td>200</td>
<td>64 %</td>
<td>100 %</td>
<td>26 %</td>
<td>26 %</td>
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<td>26 %</td>
<td>26 %</td>
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</tr>
<tr>
<td></td>
<td>300 s</td>
<td>110 s</td>
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<td>110 s</td>
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</tr>
<tr>
<td>300</td>
<td>72 %</td>
<td>100 %</td>
<td>39 %</td>
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<td>39 %</td>
<td>39 %</td>
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<td>140 s</td>
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<tr>
<td>400</td>
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<td>100 %</td>
<td>77 %</td>
<td>77 %</td>
<td>77 %</td>
<td>77 %</td>
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</tr>
<tr>
<td></td>
<td>300 s</td>
<td>180 s</td>
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<td>180 s</td>
<td>180 s</td>
<td>180 s</td>
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<td>180 s</td>
</tr>
<tr>
<td>500</td>
<td>97 %</td>
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<td>87 %</td>
<td>87 %</td>
<td>87 %</td>
<td>87 %</td>
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<td>87 %</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>220 s</td>
<td>220 s</td>
<td>220 s</td>
<td>220 s</td>
<td>220 s</td>
<td>220 s</td>
<td>220 s</td>
</tr>
</tbody>
</table>

a. Percent of area with $\text{H}_2\text{S}$ concentration $\geq 50$ ppm during the first 300s of pit and barn ventilation.

b. Duration of time with $\text{H}_2\text{S}$ concentration $\geq 50$ ppm during the first 300s of pit and barn ventilation.

c. Maximum $\text{H}_2\text{S}$ concentration during the first 300s of pit and barn ventilation.

d. Manure pit-safety ventilation duration required to reach a maximum pit $\text{H}_2\text{S}$ concentration of 10 ppm.

e. Manure pit-safety ventilation duration required to reach a maximum pit $\text{H}_2\text{S}$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 7.13. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV21Qr120 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 % $^a$</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>18 %</td>
<td>752 s $^d$</td>
<td>1,266 s $^e$</td>
</tr>
<tr>
<td></td>
<td>130 s $^b$</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>48 ppm</td>
<td>50 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ppm $^c$</td>
<td>49 ppm</td>
<td>19 ppm</td>
<td>23 ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>12 %</td>
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<td>58 %</td>
<td>756 s</td>
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<td></td>
</tr>
<tr>
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<td>50 ppm</td>
<td>19 ppm</td>
<td>23 ppm</td>
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<td></td>
</tr>
<tr>
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<td>25 %</td>
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<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
<td>769 s</td>
<td>1,282 s</td>
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<tr>
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<td>31 %</td>
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<td>1,331 s</td>
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<td>277 s</td>
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<td>74 ppm</td>
<td>28 ppm</td>
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<td>97 %</td>
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<td>1,397 s</td>
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<tr>
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<td>0 s</td>
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<td>274 s</td>
<td>291 s</td>
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<td></td>
<td>100 ppm</td>
<td>98 ppm</td>
<td>38 ppm</td>
<td>45 ppm</td>
<td>96 ppm</td>
<td>100 ppm</td>
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<td>200</td>
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<tr>
<td></td>
<td>61 %</td>
<td>100 %</td>
<td>15 %</td>
<td>3 %</td>
<td>88 %</td>
<td>100 %</td>
<td>1,099 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>130 s</td>
<td>20 s</td>
<td>80 s</td>
<td>288 s</td>
<td>293 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>197 ppm</td>
<td>75 ppm</td>
<td>91 ppm</td>
<td>192 ppm</td>
<td>200 ppm</td>
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<td>288 s</td>
<td>294 s</td>
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<td></td>
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<tr>
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<td>300 ppm</td>
<td>295 ppm</td>
<td>113 ppm</td>
<td>136 ppm</td>
<td>288 ppm</td>
<td>300 ppm</td>
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<td>400</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>84 %</td>
<td>100 %</td>
<td>64 %</td>
<td>55 %</td>
<td>100 %</td>
<td>100 %</td>
<td>1,220 s</td>
<td>-</td>
</tr>
<tr>
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<td>300 s</td>
<td>180 s</td>
<td>120 s</td>
<td>205 s</td>
<td>288 s</td>
<td>295 s</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>400 ppm</td>
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<td>151 ppm</td>
<td>182 ppm</td>
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<td>400 ppm</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>95 %</td>
<td>100 %</td>
<td>82 %</td>
<td>95 %</td>
<td>100 %</td>
<td>100 %</td>
<td>1,266 s</td>
<td>-</td>
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<td></td>
<td>300 s</td>
<td>210 s</td>
<td>180 s</td>
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<td>290 s</td>
<td>295 s</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>492 ppm</td>
<td>188 ppm</td>
<td>227 ppm</td>
<td>480 ppm</td>
<td>500 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
The following were observed for simulation case CV21:

1. Quintile I was never completely clear for all three $Q_{ratios}$, even when $C_0 = 50$ ppm, and was 100% contaminated for all three $Q_{ratios}$ when $C_0 \geq 75$ ppm.

2. Quintile II was 1% contaminated when $C_0 = 51$ ppm for Qr30, and 2% contaminated when $C_0 = 55$ ppm for Qr60 and 120. Quintile II was 100% contaminated when $C_0 \geq 300$ ppm for all three $Q_{ratios}$.

3. Quintile III was not contaminated when $C_0 \leq 100$ ppm for all three $Q_{ratios}$. Quintile III was 100%, 97%, and 95% contaminated when $C_0 = 500$ ppm for Qr30, 60, and 120, respectively.

4. Quintile IV was not contaminated when $C_0 \leq 100$ ppm for all three $Q_{ratios}$. Quintile IV was 94%, 87%, and 82% contaminated when $C_0 = 500$ ppm for Qr30, 60, and 120, respectively.

5. Quintile V was only 5%, 2%, and 2% contaminated when $C_0 = 51$ ppm inside the manure pit for Qr30, 60, and 120, respectively. Quintile V was 100% contaminated with $C(H_2S) \geq 50$ ppm when $C_0 \geq 200$ ppm inside the manure pit for all three $Q_{ratios}$. 
7.3.2.5 CV22

Simulation cases for pit-safety fan location (2,2) were performed using $Q_{\text{ratio}}$ of 30, 60, and 120. Figure 7.24 illustrates the air flow pattern across the barn and manure pit at the centerline of the pit-safety ventilation fan at location (2,2) for Qr30. Figure 7.25 and Figure 7.26 show isometric views of 3D gas contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace for CV simulation case location (2,2) and Qr30 at times 30s, 60s, 120s, 180s, 300s, and 600s after the start of pit and barn ventilation for initial manure pit $\text{H}_2\text{S}$ concentrations of 100 ppm and 500 ppm.

![Barn Airflow](image)

Figure 7.24. Right cross section showing velocity vectors at the centerline of the pit-safety ventilation fan at CV simulation case location (2,2) and Qr30 when time = 300s.
Figure 7.25. Isometric views of 3D gas contours where C(H₂S) = 50 ppm in the barn airspace for CV simulation case CV22Qr30 and initial manure pit H₂S concentrations of (a) 100 ppm and (b) 500 ppm at times 30s, 60s, and 120s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where C(H₂S) = 50 ppm in the barn airspace; C(H₂S) > 50 ppm beneath the red surfaces.
Figure 7.26. Isometric views of 3D gas contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace for CV simulation case CV22Qr30 and initial manure pit $\text{H}_2\text{S}$ concentrations of (a) 100 ppm and (b) 500 ppm at times 180s, 300s, and 600s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace; $C(\text{H}_2\text{S}) > 50$ ppm beneath the red surfaces.
Figure 7.27 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation with initial manure pit H\textsubscript{2}S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (2,2) and Q\textsubscript{ratio} 30, 60, and 120. Table 7.14, Table 7.15, and Table 7.16 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (2,2) and Q\textsubscript{ratio} 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H\textsubscript{2}S) ≥ 50 ppm, duration of time when C(H\textsubscript{2}S) ≥ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H\textsubscript{2}S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.
Figure 7.27. Plot showing contaminated areas on the CV barn measurement plane during barn and pit-safety ventilation for case CV22.
Table 7.14. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV22Qr30 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3 %$^a$</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1 %</td>
<td>14 %</td>
<td>402 s$^d$</td>
<td>809 s$^e$</td>
</tr>
<tr>
<td></td>
<td>60 s$^b$</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>30 s</td>
<td>60 s</td>
<td>50 ppm</td>
<td>50 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>49 ppm</td>
<td>20 ppm</td>
<td>47 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>8 %</td>
<td>2 %</td>
<td>0 %</td>
<td>0 %</td>
<td>7 %</td>
<td>32 %</td>
<td>404 s</td>
<td>811 s</td>
</tr>
<tr>
<td></td>
<td>108 s</td>
<td>8 s</td>
<td>0 s</td>
<td>0 s</td>
<td>90 s</td>
<td>90 s</td>
<td>404 s</td>
<td>811 s</td>
</tr>
<tr>
<td></td>
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<td>50 ppm</td>
<td>20 ppm</td>
<td>48 ppm</td>
<td>51 ppm</td>
<td>51 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>23 %</td>
<td>39 %</td>
<td>0 %</td>
<td>1 %</td>
<td>23 %</td>
<td>54 %</td>
<td>423 s</td>
<td>821 s</td>
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<td>40 s</td>
<td>115 s</td>
<td>115 s</td>
<td>423 s</td>
<td>821 s</td>
</tr>
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<td>54 ppm</td>
<td>22 ppm</td>
<td>51 ppm</td>
<td>55 ppm</td>
<td>55 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>45 %</td>
<td>78 %</td>
<td>0 %</td>
<td>5 %</td>
<td>47 %</td>
<td>95 %</td>
<td>490 s</td>
<td>868 s</td>
</tr>
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<td>70 s</td>
<td>0 s</td>
<td>90 s</td>
<td>152 s</td>
<td>141 s</td>
<td>490 s</td>
<td>868 s</td>
</tr>
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<td>74 ppm</td>
<td>30 ppm</td>
<td>70 ppm</td>
<td>75 ppm</td>
<td>75 ppm</td>
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<td></td>
</tr>
<tr>
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<td>55 %</td>
<td>97 %</td>
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<td>9 %</td>
<td>70 %</td>
<td>97 %</td>
<td>548 s</td>
<td>906 s</td>
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<td>120 s</td>
<td>176 s</td>
<td>162 s</td>
<td>548 s</td>
<td>906 s</td>
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<td>40 ppm</td>
<td>94 ppm</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>69 %</td>
<td>100 %</td>
<td>27 %</td>
<td>20 %</td>
<td>96 %</td>
<td>100 %</td>
<td>671 s</td>
<td>-</td>
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<td>150 s</td>
<td>29 s</td>
<td>215 s</td>
<td>228 s</td>
<td>294 s</td>
<td>671 s</td>
<td>-</td>
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<td>79 ppm</td>
<td>187 ppm</td>
<td>200 ppm</td>
<td>200 ppm</td>
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<tr>
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<td>100 %</td>
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<td>42 %</td>
<td>100 %</td>
<td>100 %</td>
<td>734 s</td>
<td>-</td>
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<td>271 s</td>
<td>295 s</td>
<td>734 s</td>
<td>-</td>
</tr>
<tr>
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<td>300 ppm</td>
<td>295 ppm</td>
<td>119 ppm</td>
<td>281 ppm</td>
<td>300 ppm</td>
<td>300 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>94 %</td>
<td>100 %</td>
<td>80 %</td>
<td>88 %</td>
<td>100 %</td>
<td>100 %</td>
<td>775 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>260 s</td>
<td>200 s</td>
<td>282 s</td>
<td>291 s</td>
<td>295 s</td>
<td>775 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>393 ppm</td>
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<td>374 ppm</td>
<td>400 ppm</td>
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<td></td>
</tr>
<tr>
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<td>98 %</td>
<td>100 %</td>
<td>94 %</td>
<td>98 %</td>
<td>100 %</td>
<td>100 %</td>
<td>809 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>300 s</td>
<td>230 s</td>
<td>283 s</td>
<td>292 s</td>
<td>295 s</td>
<td>809 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>492 ppm</td>
<td>199 ppm</td>
<td>468 ppm</td>
<td>500 ppm</td>
<td>500 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: “-” indicates that the simulation ended before $T_{pel}$ was reached.
Table 7.15. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV22Qr60 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
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<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3 %$^a$</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>13 %</td>
<td>428 s$^d$</td>
<td>777 s$^e$</td>
</tr>
<tr>
<td></td>
<td>70 s$^b$</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>70 s</td>
<td>50 ppm</td>
<td>50 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>49 ppm</td>
<td>18 ppm</td>
<td>40 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>7 %</td>
<td>2 %</td>
<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
<td>13 %</td>
<td>33 %</td>
<td>430 s</td>
</tr>
<tr>
<td></td>
<td>128 s</td>
<td>8 s</td>
<td>0 s</td>
<td>0 s</td>
<td>60 s</td>
<td>120 s</td>
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</tr>
<tr>
<td></td>
<td>178 s</td>
<td>38 s</td>
<td>0 s</td>
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<td>140 s</td>
<td>140 s</td>
<td>140 s</td>
<td>140 s</td>
</tr>
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<td></td>
<td>55 ppm</td>
<td>54 ppm</td>
<td>19 ppm</td>
<td>44 ppm</td>
<td>55 ppm</td>
<td>55 ppm</td>
<td>55 ppm</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>43 %</td>
<td>77 %</td>
<td>0 %</td>
<td>1 %</td>
<td>44 %</td>
<td>95 %</td>
<td>483 s</td>
<td>841 s</td>
</tr>
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<td>220 s</td>
<td>60 s</td>
<td>0 s</td>
<td>40 s</td>
<td>192 s</td>
<td>170 s</td>
<td>170 s</td>
<td>170 s</td>
</tr>
<tr>
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<td>75 ppm</td>
<td>74 ppm</td>
<td>26 ppm</td>
<td>60 ppm</td>
<td>75 ppm</td>
<td>75 ppm</td>
<td>75 ppm</td>
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</tr>
<tr>
<td>100</td>
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<td>97 %</td>
<td>0 %</td>
<td>4 %</td>
<td>66 %</td>
<td>100 %</td>
<td>521 s</td>
<td>891 s</td>
</tr>
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<td></td>
<td>250 s</td>
<td>80 s</td>
<td>0 s</td>
<td>120 s</td>
<td>224 s</td>
<td>182 s</td>
<td>182 s</td>
<td>182 s</td>
</tr>
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<td>98 ppm</td>
<td>35 ppm</td>
<td>80 ppm</td>
<td>100 ppm</td>
<td>100 ppm</td>
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<td></td>
</tr>
<tr>
<td>200</td>
<td>65 %</td>
<td>100 %</td>
<td>21 %</td>
<td>9 %</td>
<td>97 %</td>
<td>100 %</td>
<td>622 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>140 s</td>
<td>24 s</td>
<td>260 s</td>
<td>288 s</td>
<td>264 s</td>
<td>264 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>197 ppm</td>
<td>70 ppm</td>
<td>160 ppm</td>
<td>199 ppm</td>
<td>200 ppm</td>
<td>200 ppm</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>72 %</td>
<td>100 %</td>
<td>37 %</td>
<td>22 %</td>
<td>100 %</td>
<td>100 %</td>
<td>691 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>170 s</td>
<td>109 s</td>
<td>275 s</td>
<td>288 s</td>
<td>294 s</td>
<td>294 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>295 ppm</td>
<td>105 ppm</td>
<td>240 ppm</td>
<td>299 ppm</td>
<td>300 ppm</td>
<td>300 ppm</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>88 %</td>
<td>100 %</td>
<td>67 %</td>
<td>72 %</td>
<td>100 %</td>
<td>100 %</td>
<td>739 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>220 s</td>
<td>199 s</td>
<td>281 s</td>
<td>290 s</td>
<td>295 s</td>
<td>295 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>393 ppm</td>
<td>140 ppm</td>
<td>320 ppm</td>
<td>399 ppm</td>
<td>400 ppm</td>
<td>400 ppm</td>
<td></td>
</tr>
<tr>
<td>500</td>
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<td>100 %</td>
<td>87 %</td>
<td>96 %</td>
<td>100 %</td>
<td>100 %</td>
<td>777 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>270 s</td>
<td>250 s</td>
<td>281 s</td>
<td>291 s</td>
<td>295 s</td>
<td>295 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
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<td>492 ppm</td>
<td>175 ppm</td>
<td>400 ppm</td>
<td>499 ppm</td>
<td>500 ppm</td>
<td>500 ppm</td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration $\geq$ 50 ppm during the first 300 s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration $\geq$ 50 ppm during the first 300 s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300 s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 7.16. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV22Qr120 with $T_{pel}$ values.

<table>
<thead>
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<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2 %$^a$</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>12 %</td>
<td>568 s$^d$</td>
<td>807 s$^e$</td>
</tr>
<tr>
<td></td>
<td>90 s$^b$</td>
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<td>90 s</td>
<td>50 ppm</td>
</tr>
<tr>
<td></td>
<td>50 ppm$^c$</td>
<td>49 ppm</td>
<td>17 ppm</td>
<td>24 ppm</td>
<td>48 ppm</td>
<td>90 s</td>
<td>50 ppm</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>9 %</td>
<td>2 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>43 %</td>
<td>569 s</td>
<td>809 s</td>
</tr>
<tr>
<td></td>
<td>158 s</td>
<td>8 s</td>
<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>150 s</td>
<td>51 ppm</td>
<td>51 ppm</td>
</tr>
<tr>
<td></td>
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<td>50 ppm</td>
<td>17 ppm</td>
<td>25 ppm</td>
<td>49 ppm</td>
<td>51 ppm</td>
<td>51 ppm</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>25 %</td>
<td>42 %</td>
<td>17 ppm</td>
<td>0 %</td>
<td>2 %</td>
<td>79 %</td>
<td>576 s</td>
<td>820 s</td>
</tr>
<tr>
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<td>38 s</td>
<td>0 s</td>
<td>0 s</td>
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<td>200 s</td>
<td>55 ppm</td>
<td>55 ppm</td>
</tr>
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<td>54 ppm</td>
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<td>27 ppm</td>
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<td>55 ppm</td>
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<td></td>
</tr>
<tr>
<td>75</td>
<td>44 %</td>
<td>74 %</td>
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<td>0 %</td>
<td>47 %</td>
<td>100 %</td>
<td>604 s</td>
<td>869 s</td>
</tr>
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<td>0 s</td>
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<td>220 s</td>
<td>249 s</td>
<td>604 s</td>
<td>869 s</td>
</tr>
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<td></td>
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<td>74 ppm</td>
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<td>37 ppm</td>
<td>72 ppm</td>
<td>75 ppm</td>
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</tr>
<tr>
<td>100</td>
<td>51 %</td>
<td>92 %</td>
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<td>64 %</td>
<td>100 %</td>
<td>635 s</td>
<td>926 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>80 s</td>
<td>0 s</td>
<td>0 s</td>
<td>264 s</td>
<td>281 s</td>
<td>635 s</td>
<td>926 s</td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
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<td>34 ppm</td>
<td>49 ppm</td>
<td>96 ppm</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>64 %</td>
<td>100 %</td>
<td>16 %</td>
<td>4 %</td>
<td>98 %</td>
<td>100 %</td>
<td>697 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>130 s</td>
<td>18 s</td>
<td>190 s</td>
<td>288 s</td>
<td>294 s</td>
<td>697 s</td>
<td>-</td>
</tr>
<tr>
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<td>200 ppm</td>
<td>197 ppm</td>
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<td>98 ppm</td>
<td>193 ppm</td>
<td>290 ppm</td>
<td>200 ppm</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>67 %</td>
<td>100 %</td>
<td>26 %</td>
<td>10 %</td>
<td>100 %</td>
<td>100 %</td>
<td>742 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>170 s</td>
<td>39 s</td>
<td>275 s</td>
<td>288 s</td>
<td>294 s</td>
<td>742 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>295 ppm</td>
<td>102 ppm</td>
<td>146 ppm</td>
<td>289 ppm</td>
<td>300 ppm</td>
<td>300 ppm</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>89 %</td>
<td>100 %</td>
<td>70 %</td>
<td>74 %</td>
<td>100 %</td>
<td>100 %</td>
<td>772 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>210 s</td>
<td>139 s</td>
<td>280 s</td>
<td>290 s</td>
<td>295 s</td>
<td>772 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>393 ppm</td>
<td>136 ppm</td>
<td>195 ppm</td>
<td>385 ppm</td>
<td>400 ppm</td>
<td>400 ppm</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>96 %</td>
<td>100 %</td>
<td>81 %</td>
<td>97 %</td>
<td>100 %</td>
<td>100 %</td>
<td>807 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>230 s</td>
<td>179 s</td>
<td>281 s</td>
<td>290 s</td>
<td>295 s</td>
<td>807 s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>492 ppm</td>
<td>170 ppm</td>
<td>244 ppm</td>
<td>482 ppm</td>
<td>500 ppm</td>
<td>500 ppm</td>
<td></td>
</tr>
</tbody>
</table>

- $a$. Percent of area with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
- $b$. Duration of time with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
- $c$. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
- $d$. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
- $e$. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
The following were observed for simulation case CV22:

1. Quintile I was never completely clear for all three Q_{ratios}, even when C_{0} = 50 ppm. Quintile I was 100% contaminated when C_{0} ≥ 200 ppm, 100 ppm, and 75 ppm for Q_{r30}, 60, and 120, respectively.

2. Quintile II was 1% contaminated when C_{0} = 50 ppm for Q_{r30}, 2% contaminated when C_{0} = 51 ppm for Q_{r60}, and 2% contaminated when C_{0} = 55 ppm for Q_{r120}. Quintile II was 100% contaminated when C_{0} ≥ 300 ppm for all three Q_{ratios}.

3. Quintile III became contaminated at lower C_{0} values as Q_{ratio} decreased (pit-safety fan flow rate increased). Quintile III was 98%, 96%, and 97% contaminated when C_{0} = 500 ppm for Q_{r30}, 60, and 120, respectively.

4. Quintile IV was not contaminated when C_{0} ≤ 100 ppm for all three Q_{ratios}. Quintile IV was 94%, 87%, and 81% contaminated when C_{0} = 500 ppm for Q_{r30}, 60, and 120, respectively.

5. Quintile V was only 2% contaminated when C_{0} = 51 ppm inside the manure pit for all three Q_{ratios}. Quintile V was 100% contaminated with C(H_{2}S) ≥ 50 ppm when C_{0} ≥ 200 ppm inside the manure pit for all three Q_{ratios}.
Simulation cases for pit-safety fan location (2,3) were performed using $Q_{\text{ratio}}$ of 30, 60, and 120. Figure 7.28 illustrates the air flow pattern across the barn and manure pit at the centerline of the pit-safety ventilation fan at location (2,3) for $Q_{\text{r}30}$. Figure 7.29 and Figure 7.30 show isometric views of 3D gas contours where $C(\text{H}_2\text{S}) = 50$ ppm in the barn airspace for CV simulation case location (2,3) and $Q_{\text{r}30}$ at times 30s, 60s, 120s, 180s, 300s, and 600s after the start of pit and barn ventilation for initial manure pit $\text{H}_2\text{S}$ concentrations of 100 ppm and 500 ppm.

Figure 7.28. Right cross section showing velocity vectors at the centerline of the pit-safety ventilation fan at CV simulation case location (2,3) and $Q_{\text{r}30}$ when time = 300s.
Figure 7.29. Isometric views of 3D gas contours where C(H2S) = 50 ppm in the barn airspace for CV simulation case CV23Qr30 and initial manure pit H2S concentrations of (a) 100 ppm and (b) 500 ppm at times 30s, 60s, and 120s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where C(H2S) = 50 ppm in the barn airspace; C(H2S) > 50 ppm beneath the red surfaces.
Figure 7.30. Isometric views of 3D gas contours where $C(H_2S) = 50$ ppm in the barn airspace for CV simulation case CV23Qr30 and initial manure pit $H_2S$ concentrations of (a) 100 ppm and (b) 500 ppm at times 180s, 300s, and 600s after the start of pit and barn ventilation.

Notes: Grid line spacing is 0.6 m (2 ft); red surfaces show 3D contours where $C(H_2S) = 50$ ppm in the barn airspace; $C(H_2S) > 50$ ppm beneath the red surfaces.
Figure 7.31 shows the contaminated barn area on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation with initial manure pit H$_2$S concentrations equal to 100, 200, 300, 400, and 500 ppm for pit-safety fan location (2,3) and Q$_{ratios}$ 30, 60, and 120. Table 7.17, Table 7.18, and Table 7.19 list comparison statistics for several initial manure pit concentration values for pit-safety fan location (2,3) and Q$_{ratios}$ 30, 60, and 120, respectively. The statistics include the percentage of contaminated area where C(H$_2$S) $\geq$ 50 ppm, duration of time when C(H$_2$S) $\geq$ 50 ppm, and the maximum concentration on the measurement plane 0.15 m (6 in.) above the slotted floor during the first 300s of barn and pit-safety ventilation. The table presents the statistics for the barn overall, then for each quintile. The last column in the table lists the duration of manure pit-safety ventilation required to reach a maximum H$_2$S concentration of 10 or 1 ppm anywhere inside the manure pit airspace.
Figure 7.31. Plot showing contaminated areas on the CV barn measurement plane during barn and pit-safety ventilation for case CV23.
Table 7.17. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV23Qr30 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>V</th>
<th>IV</th>
<th>III</th>
<th>II</th>
<th>I</th>
<th>$T_{pel(10)}$</th>
<th>$T_{pel(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>2 %</td>
<td>320 s</td>
<td>717 s</td>
</tr>
<tr>
<td></td>
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<td>0 s</td>
<td>0 s</td>
<td>0 s</td>
<td>20 s</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>50 ppm c</td>
<td>49 ppm</td>
<td>19 ppm</td>
<td>38 ppm</td>
<td>50 ppm</td>
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</tr>
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</tr>
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<td>30 s</td>
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</tr>
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<td></td>
</tr>
<tr>
<td>55</td>
<td>17 %</td>
<td>42 %</td>
<td>0 %</td>
<td>0 %</td>
<td>12 %</td>
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<td>335 s</td>
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</tr>
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<td>77 s</td>
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<td>55 s</td>
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<td>54 ppm</td>
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<td>42 ppm</td>
<td>55 ppm</td>
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</tr>
<tr>
<td>75</td>
<td>40 %</td>
<td>78 %</td>
<td>0 %</td>
<td>1 %</td>
<td>43 %</td>
<td>78 %</td>
<td>382 s</td>
<td>790 s</td>
</tr>
<tr>
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<td>70 s</td>
<td>0 s</td>
<td>30 s</td>
<td>144 s</td>
<td>124 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>74 ppm</td>
<td>28 ppm</td>
<td>57 ppm</td>
<td>74 ppm</td>
<td>75 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>49 %</td>
<td>94 %</td>
<td>0 %</td>
<td>5 %</td>
<td>64 %</td>
<td>83 %</td>
<td>426 s</td>
<td>838 s</td>
</tr>
<tr>
<td></td>
<td>190 s</td>
<td>90 s</td>
<td>0 s</td>
<td>120 s</td>
<td>176 s</td>
<td>145 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>98 ppm</td>
<td>37 ppm</td>
<td>76 ppm</td>
<td>99 ppm</td>
<td>100 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>64 %</td>
<td>100 %</td>
<td>25 %</td>
<td>19 %</td>
<td>88 %</td>
<td>91 %</td>
<td>548 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>250 s</td>
<td>160 s</td>
<td>23 s</td>
<td>180 s</td>
<td>240 s</td>
<td>206 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>197 ppm</td>
<td>74 ppm</td>
<td>151 ppm</td>
<td>198 ppm</td>
<td>200 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>72 %</td>
<td>100 %</td>
<td>37 %</td>
<td>36 %</td>
<td>94 %</td>
<td>96 %</td>
<td>623 s</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>210 s</td>
<td>149 s</td>
<td>235 s</td>
<td>290 s</td>
<td>258 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>295 ppm</td>
<td>111 ppm</td>
<td>227 ppm</td>
<td>298 ppm</td>
<td>300 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>84 %</td>
<td>100 %</td>
<td>56 %</td>
<td>67 %</td>
<td>96 %</td>
<td>99 %</td>
<td>676 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>240 s</td>
<td>209 s</td>
<td>275 s</td>
<td>291 s</td>
<td>288 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>393 ppm</td>
<td>148 ppm</td>
<td>302 ppm</td>
<td>397 ppm</td>
<td>400 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>89 %</td>
<td>100 %</td>
<td>74 %</td>
<td>76 %</td>
<td>96 %</td>
<td>99 %</td>
<td>717 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>270 s</td>
<td>239 s</td>
<td>275 s</td>
<td>291 s</td>
<td>299 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>492 ppm</td>
<td>185 ppm</td>
<td>378 ppm</td>
<td>496 ppm</td>
<td>500 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with $H_2S$ concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum $H_2S$ concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit $H_2S$ concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 7.18. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV23Qr60 with $T_{pel}$ values.

<table>
<thead>
<tr>
<th>$C_0$ (ppm)</th>
<th>Overall</th>
<th>Barn Quintile <em>(For first 300s)</em></th>
<th>$T_{pel}(10)$</th>
<th>$T_{pel}(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0 % a</td>
<td>0 %</td>
<td>2 %</td>
<td>330 s; 626 s</td>
</tr>
<tr>
<td></td>
<td>20 s b</td>
<td>0 s</td>
<td>20 s</td>
<td>626 s; 629 s</td>
</tr>
<tr>
<td></td>
<td>50 ppm c</td>
<td>17 ppm</td>
<td>50 ppm</td>
<td>50 ppm</td>
</tr>
<tr>
<td>51</td>
<td>4 %</td>
<td>2 %</td>
<td>2 %</td>
<td>332 s; 629 s</td>
</tr>
<tr>
<td></td>
<td>58 s</td>
<td>0 s</td>
<td>20 s</td>
<td>50 s</td>
</tr>
<tr>
<td></td>
<td>51 ppm</td>
<td>18 ppm</td>
<td>51 ppm</td>
<td>51 ppm</td>
</tr>
<tr>
<td>55</td>
<td>17 %</td>
<td>42 %</td>
<td>7 %</td>
<td>342 s; 640 s</td>
</tr>
<tr>
<td></td>
<td>87 s</td>
<td>37 %</td>
<td>60 s</td>
<td>60 s</td>
</tr>
<tr>
<td></td>
<td>55 ppm</td>
<td>19 ppm</td>
<td>55 ppm</td>
<td>55 ppm</td>
</tr>
<tr>
<td>75</td>
<td>40 %</td>
<td>75 %</td>
<td>40 %</td>
<td>380 s; 681 s</td>
</tr>
<tr>
<td></td>
<td>160 s</td>
<td>0 %</td>
<td>142 s</td>
<td>151 s</td>
</tr>
<tr>
<td></td>
<td>75 ppm</td>
<td>26 ppm</td>
<td>75 ppm</td>
<td>75 ppm</td>
</tr>
<tr>
<td>100</td>
<td>49 %</td>
<td>94 %</td>
<td>57 %</td>
<td>415 s; 724 s</td>
</tr>
<tr>
<td></td>
<td>200 s</td>
<td>80 %</td>
<td>186 s</td>
<td>173 s</td>
</tr>
<tr>
<td></td>
<td>100 ppm</td>
<td>35 ppm</td>
<td>99 ppm</td>
<td>100 ppm</td>
</tr>
<tr>
<td>200</td>
<td>64 %</td>
<td>100 %</td>
<td>91 %</td>
<td>497 s</td>
</tr>
<tr>
<td></td>
<td>280 s</td>
<td>18 %</td>
<td>268 s</td>
<td>265 s</td>
</tr>
<tr>
<td></td>
<td>200 ppm</td>
<td>69 ppm</td>
<td>260 s</td>
<td>200 s</td>
</tr>
<tr>
<td>300</td>
<td>72 %</td>
<td>100 %</td>
<td>97 %</td>
<td>555 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>37 %</td>
<td>97 %</td>
<td>99 %</td>
</tr>
<tr>
<td></td>
<td>300 ppm</td>
<td>104 ppm</td>
<td>295 s</td>
<td>-</td>
</tr>
<tr>
<td>400</td>
<td>82 %</td>
<td>100 %</td>
<td>98 %</td>
<td>595 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>50 %</td>
<td>100 %</td>
<td>100 %</td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
<td>139 ppm</td>
<td>297 s</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>90 %</td>
<td>100 %</td>
<td>100 %</td>
<td>626 s</td>
</tr>
<tr>
<td></td>
<td>300 s</td>
<td>73 %</td>
<td>100 %</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>500 ppm</td>
<td>173 ppm</td>
<td>500 ppm</td>
<td>-</td>
</tr>
</tbody>
</table>

a. Percent of area with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
b. Duration of time with H$_2$S concentration $\geq$ 50 ppm during the first 300s of pit and barn ventilation.
c. Maximum H$_2$S concentration during the first 300s of pit and barn ventilation.
d. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 10 ppm.
e. Manure pit-safety ventilation duration required to reach a maximum pit H$_2$S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before $T_{pel}$ was reached.
Table 7.19. Contaminated area, time, and maximum concentration on the barn measurement plane during the first 300 s of barn and pit ventilation for case CV23Qr120 with T_{pel} values.

<table>
<thead>
<tr>
<th>C_0 (ppm)</th>
<th>Overall</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>T_{pel(10)}</th>
<th>T_{pel(1)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 % (^a)</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>7 %</td>
<td>424 s (^d)</td>
</tr>
<tr>
<td>4 %</td>
<td>2 %</td>
<td>0 %</td>
<td>0 %</td>
<td>28 ppm</td>
<td>0 s</td>
<td>49 ppm</td>
<td>18 %</td>
<td>426 s</td>
</tr>
<tr>
<td>108 s</td>
<td>8 s</td>
<td>0 s</td>
<td>29 ppm</td>
<td>0 s</td>
<td>50 ppm</td>
<td>51 ppm</td>
<td>436 s</td>
<td>839 s</td>
</tr>
<tr>
<td>18 %</td>
<td>42 %</td>
<td>0 %</td>
<td>0 %</td>
<td>31 ppm</td>
<td>0 s</td>
<td>54 ppm</td>
<td>46 %</td>
<td>493 s</td>
</tr>
<tr>
<td>39 %</td>
<td>74 %</td>
<td>0 %</td>
<td>0 %</td>
<td>42 ppm</td>
<td>0 s</td>
<td>74 ppm</td>
<td>85 %</td>
<td>500 ppm</td>
</tr>
<tr>
<td>240 s</td>
<td>60 s</td>
<td>0 s</td>
<td>0 %</td>
<td>420 s</td>
<td>192 s</td>
<td>215 s</td>
<td>262 s</td>
<td>534 s</td>
</tr>
<tr>
<td>75</td>
<td>50 %</td>
<td>92 %</td>
<td>0 %</td>
<td>63 %</td>
<td>254 s</td>
<td>99 ppm</td>
<td>100 ppm</td>
<td>650 s</td>
</tr>
<tr>
<td>100</td>
<td>270 s</td>
<td>80 s</td>
<td>110 s</td>
<td>295 s</td>
<td>300 ppm</td>
<td>295 s</td>
<td>100 ppm</td>
<td>779 s</td>
</tr>
<tr>
<td>200</td>
<td>62 %</td>
<td>100 %</td>
<td>15 %</td>
<td>92 %</td>
<td>288 s</td>
<td>294 s</td>
<td>295 s</td>
<td>829 s</td>
</tr>
<tr>
<td>300 s</td>
<td>130 s</td>
<td>17 s</td>
<td>240 s</td>
<td>197 ppm</td>
<td>400 ppm</td>
<td>200 ppm</td>
<td>829 s</td>
<td></td>
</tr>
<tr>
<td>300 ppm</td>
<td>170 s</td>
<td>108 s</td>
<td>270 s</td>
<td>120 ppm</td>
<td>493 ppm</td>
<td>400 ppm</td>
<td>829 s</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>83 %</td>
<td>100 %</td>
<td>49 %</td>
<td>64 %</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>829 s</td>
</tr>
<tr>
<td>300 s</td>
<td>230 s</td>
<td>199 s</td>
<td>275 s</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>100 ppm</td>
<td>829 s</td>
</tr>
<tr>
<td>400 ppm</td>
<td>394 ppm</td>
<td>136 ppm</td>
<td>225 ppm</td>
<td>197 ppm</td>
<td>500 ppm</td>
<td>500 ppm</td>
<td>500 ppm</td>
<td></td>
</tr>
</tbody>
</table>

a. Percent of area with H_2S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.

b. Duration of time with H_2S concentration ≥ 50 ppm during the first 300s of pit and barn ventilation.

c. Maximum H_2S concentration during the first 300s of pit and barn ventilation.

d. Manure pit-safety ventilation duration required to reach a maximum pit H_2S concentration of 10 ppm.

e. Manure pit-safety ventilation duration required to reach a maximum pit H_2S concentration of 1 ppm.

Note: "-" indicates that the simulation ended before T_{pel} was reached.
The following were observed for simulation case CV23:

1. Quintile I was never completely clear for all three Q\text{ratios}, even when \( C_0 = 50 \text{ ppm} \). Quintile I was 99% contaminated when \( C_0 = 500 \text{ ppm} \) for Qr30. Quintile I was 100% contaminated when \( C_0 \geq 400 \text{ ppm} \) and 300 ppm for Qr60 and 120, respectively.

2. Quintile II was 4%, 2%, and 1% contaminated when \( C_0 = 50 \text{ ppm} \) for Qr30, 60, and 120, respectively. Quintile II was 100% contaminated when \( C_0 \geq 300 \text{ ppm} \) for all three Q\text{ratios}. Quintile II was 96% contaminated when \( C_0 = 500 \text{ ppm} \) for Qr30. Quintile I was 100% contaminated when \( C_0 \geq 500 \text{ ppm} \) and 400 ppm for Qr60 and 120, respectively.

3. Quintile III was not contaminated when \( C_0 \leq 55 \text{ ppm} \) for Qr30 and 60, and when \( C_0 \leq 75 \text{ ppm} \) for Qr120. Quintile III was 76%, 76%, and 74% contaminated when \( C_0 = 500 \text{ ppm} \) for Qr30, 60, and 120, respectively.

4. Quintile IV was not contaminated when \( C_0 \leq 100 \text{ ppm} \) for all three Q\text{ratios}. Quintile IV was 74%, 73%, and 70% contaminated when \( C_0 = 500 \text{ ppm} \) for Qr30, 60, and 120, respectively.

5. Quintile V was only 2% contaminated when \( C_0 = 51 \text{ ppm} \) inside the manure pit for all three Q\text{ratios}. Quintile V was 100% contaminated with \( C(\text{H}_2\text{S}) \geq 50 \text{ ppm} \) when \( C_0 \geq 200 \text{ ppm} \) inside the manure pit for all three Q\text{ratios}. 
7.4 Discussion of results

This section presents a discussion of the effects of different pit-safety ventilation fan locations and \( Q_{\text{ratio}} \) for cross-ventilated barns on the contaminated area and duration of time when \( C(H_2S) \geq 50 \text{ ppm} \) in the barn airspace, the maximum \( H_2S \) concentration in the barn and within each quintile, and the duration of time required to reach \( T_{\text{pel}} \) during pit and barn ventilation. This discussion is for a specific barn size, ventilation configuration, and simulated initial and boundary conditions. Other barn sizes and ventilation configurations may result in clear zones large enough to safely relocate animals temporarily during pit and barn ventilation events. Analysis of contaminated areas within the barn airspace focused on a plane located 0.15 m (6 in.) above the barn floor and did not consider the recirculation of contaminant gases from other areas in the barn above that plane. However, the observed presence of recirculation patterns in mechanically cross-ventilated barns may result in quintiles where \( C(H_2S) \geq 50 \text{ ppm} \) at elevations above the 0.15 m (6 in.) plane, even after the 0.15 m (6 in.) plane appears clear of contamination.

7.4.1 Contaminated barn area where \( C(H_2S) \geq 50 \text{ ppm} \)

Figure 7.32, Figure 7.33, Figure 7.34 and show the percentage of contaminated barn area overall and within each quintile for all pit-safety fan locations for \( Qr30 \), 60, and 120, respectively, for initial \( H_2S \) concentrations of 50, 100, and 500 ppm inside the manure pit. For all three \( Q_{\text{ratio}} \), the overall barn area was never 100\% contaminated, even when \( C_0 = 500 \text{ ppm} \). In general, as \( Q_{\text{ratio}} \) decreased (pit-safety fan flow rate increased), the percentage of contaminated overall area in the barn increased, but for all fan locations and \( Q_{\text{ratio}} \), the differences were within ±10\% of the case with no pit fan, and for some \( C_0 \) values the area percentage did not change. For example, for pit-safety fan location (1,3) when \( C_0 = 100 \text{ ppm} \), the overall percentage of barn area where \( C(H_2S) \geq 50 \text{ ppm} \) did not change, it was 49\% for \( Qr30 \), 60, and 120. Quintiles III and IV were completely clear for all pit-safety fan locations and \( Q_{\text{ratio}} \) when \( C_0 = 50 \text{ ppm} \) and had 99\% clear
area or greater when $C_0 \leq 100$ ppm, making these potentially safe zones inside the barn for animals during safety pit-safety ventilation.

Figure 7.32. Contaminated area in the barn airspace where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30 with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show $\pm 10\%$ of the value of each bar.
Figure 7.33. Contaminated area in the barn airspace where $C(\text{H}_2\text{S}) \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr60 with $C_0 = 50, 100, \text{ and } 500$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.34. Contaminated area in the barn airspace where $\text{C(H}_2\text{S)} \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for $Qr120$ with $C_0 = 50, 100,$ and $500$ ppm inside the manure pit.

Note: Error bars show $\pm10\%$ of the value of each bar.
Figure 7.35 shows the percentage of contaminated barn area in barn quintile I during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile I was never completely clear, even when C₀ = 50 ppm.
2. Quintile I was 100% contaminated when C₀ = 100 ppm for pit-safety fan locations (1,1), (2,1), and (2,2) for Qr60 and 120 and the case with no pit fan, but only for pit-safety fan locations (1,1) and (2,1) for Qr30.
3. Quintile I was not 100% contaminated when C₀ = 500 ppm for pit-safety fan locations (1,3) and (2,3) for Qr30.
Figure 7.35. Contaminated area in quintile I where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.36 shows the percentage of contaminated barn area in barn quintile II during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile II was only 1% contaminated when C₀ = 50 ppm for pit-safety fan location (2,2) for Qr30, but for all other pit-safety fan locations and Q ratios was not contaminated when C₀ = 50 ppm.

2. Quintile II was between 55% and 75% contaminated for all pit-safety fan locations and Q ratios when C₀ = 100 ppm.

3. There do not appear to be large differences between pit-safety fan locations and the case with no pit fan when C₀ = 100 ppm for Qr60 and 120 (the ±10% error bars overlap). For Qr30, pit-safety fan locations (1,1), (2,1), and (2,2) resulted in greater than 10% more contaminated barn area than the case with no pit fan.

4. Quintile II was 100% contaminated for all pit-safety fan locations and Qr60 and 120 when C₀ = 500 ppm. Quintile II was 100% contaminated for pit-safety fan locations (1,1), (2,1), and (2,2) for Qr30 and the case with no pit fan when C₀ = 500 ppm.

5. Quintile II was not 100% contaminated when C₀ = 500 ppm for pit-safety fan locations (1,3) and (2,3) for Qr30.
Figure 7.36. Contaminated area in quintile II where \( C(H_2S) \geq 50 \text{ ppm} \) during pit-safety ventilation for all CV simulation case pit-safety fan locations for \( Q_r30, 60, \) and 120, with \( C_0 = 50, 100, \) and 500 ppm inside the manure pit.

Note: Error bars show \( \pm 10\% \) of the value of each bar.
Figure 7.37 shows the percentage of contaminated barn area in barn quintile III during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile III was clear for all cases when \( C_0 = 50 \) ppm.

2. Quintile III had less than 10% contaminated area for pit-safety fan locations (2,2) and (2,3) when \( C_0 = 100 \) ppm for Qr30 and 60. Quintile III was clear for all pit-safety fan locations when \( C_0 = 100 \) ppm for Qr120.

3. Quintile III was never 100% contaminated when \( C_0 = 500 \) ppm for Qr60 and 120, but was 100% contaminated for pit-safety fan locations (1,1) and (2,1) for Qr30 when \( C_0 = 500 \) ppm.
Figure 7.37. Contaminated area in quintile III where C(H₂S) ≥ 50 ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, with C₀ = 50, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.38 shows the percentage of contaminated barn area in barn quintile IV during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H\textsubscript{2}S concentrations of 50, 100, and 500 ppm inside the manure pit. In general, it appeared that contaminated area increased as Q\textsubscript{ratio} decreased (pit-safety fan flow rate increased) for all fan locations and Q\textsubscript{ratio}. The following observations were made:

2. Quintile IV was only 1% contaminated for pit-safety fan location (1,1) and Qr30, but was clear for all cases when C\textsubscript{0} ≤ 100 ppm.

3. Quintile IV was never 100% contaminated, even when C\textsubscript{0} = 500 ppm.

4. Differences in contaminated area when C\textsubscript{0} = 500 ppm were within ±10% (the error bars overlapped) for Qr60 and 120, but for Qr30 the difference in contaminated area between cases with pit-safety fan locations (2,2) and (2,3) was greater than 10%.
Figure 7.38. Contaminated area in quintile IV where $C(\text{H}_2\text{S}) \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for $Q_{r30}$, 60, and 120, with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show $\pm 10\%$ of the value of each bar.
Figure 7.39 shows the percentage of contaminated barn area in barn quintile V during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. The following observations were made:

1. Quintile V was clear for all cases when $C_0 = 50$ ppm.
2. Quintile V was 100% contaminated for all cases when $C_0 = 500$ ppm.
3. Quintile V was greater than 80% contaminated for all cases when $C_0 = 100$ ppm, and these were within ±10% of each other (the error bars overlapped) for all pit-safety fan locations and $Q_{ratio}$. 

Figure 7.39. Contaminated area in quintile V where $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
7.4.2 Duration of time when $C(H_2S) \geq 50$ ppm

Figure 7.40, Figure 7.41, and Figure 7.42 show the duration of time the barn airspace was contaminated overall and within each quintile for all pit-safety fan locations for $Q_{r30}$, 60, and 120, respectively, for initial $H_2S$ concentrations of 50, 100, and 500 ppm inside the manure pit. The term “overall” refers to the total barn area as a whole. Overall, the duration of contamination was greater than zero for all pit-safety fan locations and $Q_{\text{ratio}}$ when the initial manure pit concentration was 50 ppm; the duration of contamination decreased as $Q_{\text{ratio}}$ decreased (pit-safety fan flow rate increased) for pit-safety fan locations (2,1) and (2,2), but the duration increased as $Q_{\text{ratio}}$ decreased for locations (1,1) and (1,3). When $C_0 = 100$ ppm, the duration of contamination in the overall barn area decreased as $Q_{\text{ratio}}$ decreased (pit-safety fan flow rate increased) for pit-safety fan locations (2,1), (2,2), and (2,3), but the duration of contamination was the full 300 s of simulated pit-safety ventilation for locations (1,1), (1,3), and the case with no pit fan. When $C_0 = 500$ ppm, the overall barn area was contaminated for the full 300 s duration of pit-safety ventilation for all fan locations and $Q_{\text{ratio}}$. 
Figure 7.40. Duration of time in the barn airspace when \( \text{C}(\text{H}_2\text{S}) \geq 50 \text{ ppm} \) during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30 with \( C_0 = 50, 100, \text{ and } 500 \text{ ppm} \) inside the manure pit.

Note: Error bars show \( \pm 10\% \) of the value of each bar.
Figure 7.41. Duration of time in the barn airspace when $C(\text{H}_2\text{S}) \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr60 with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show $\pm 10\%$ of the value of each bar.
Figure 7.42. Duration of time in the barn airspace when $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr120 with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.43 shows the duration of time the barn airspace was contaminated in quintile I during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. When the initial concentrations in the manure pit were 50 or 100 ppm, the duration of contamination in quintile I increased as Q_{ratio} decreased (pit-safety fan flow rate increased) for pit-safety fan locations (1,1) and (1,3). However, for pit-safety fan locations (2,1) and (2,2) the duration of contamination decreased as Q_{ratio} decreased (pit-safety fan flow rate increased). The duration of contamination for pit-safety fan location (2,3) decreased as Q_{ratio} decreased from Qr120 to Qr60, but did not change as Q_{ratio} decreased from Qr60 to Qr30 when C₀ = 50 ppm. When C₀ = 100 ppm, the duration of contamination for pit-safety fan location (2,3) decreased as Q_{ratio} decreased. There were no large differences in duration of contamination (the ±10% error bars overlap) when C₀ = 500 ppm for all pit-safety fan locations and Q_{ratio}, although the cases with pit-safety fan location (1,3) for Qr30 and Qr60 and location (2,3) for Qr30 were contaminated for the entire 300 s duration of simulated pit-safety ventilation.
Figure 7.43. Duration of time in quintile I when C(H₂S) ≥ 50 ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, with C₀ = 50, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.44 shows the duration of time the barn airspace was contaminated in quintile II during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H$_2$S concentrations of 50, 100, and 500 ppm inside the manure pit. When the initial manure pit concentration was 50 ppm, quintile II was only contaminated for a duration of 30 s for the case with pit-safety fan location (2,2) for Qr30. Quintile II was clear of contamination when $C_0 = 50$ ppm for all other pit-safety fan locations and $Q_{\text{ratios}}$. When $C_0 = 100$ ppm, the duration of contamination decreased as $Q_{\text{ratios}}$ decreased (pit-safety fan flow rate increased) for pit-safety fan locations (2,2) and (2,3). When $C_0 = 500$ ppm, only pit-safety fan location (1,3) resulted in contamination for the full 300 s duration of simulated pit-safety ventilation, and differences in duration were within 10% across all pit-safety fan locations and $Q_{\text{ratios}}$. 
Figure 7.44. Duration of time in quintile II when C(H₂S) ≥ 50 ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, with C₀ = 50, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.45 shows the duration of time the barn airspace was contaminated in quintile III during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. Quintile III was clear of contamination when $C_0 = 50$ ppm for all pit-safety fan locations and $Q_{ratios}$. When the initial manure pit concentration was 100 ppm, quintile III was contaminated for a duration of 120 s or shorter only for pit-safety fan locations (2,2) and (2,3) for Qr30 and 60. Quintile III was only contaminated for Qr120 for pit-safety fan location (2,3). When $C_0 = 500$ ppm, the duration of contamination in quintile III was 275 s or longer, but differences in duration were within ±10% across all fan locations and $Q_{ratios}$. 
Figure 7.45. Duration of time in quintile III when $C(H_2S) \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.46 shows the duration of time the barn airspace was contaminated in quintile IV during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H₂S concentrations of 50, 100, and 500 ppm inside the manure pit. Quintile IV was clear of contamination for all pit-safety fan locations and Q_{\text{ratios}} when the initial manure pit concentration was 50 ppm. When C_0 = 100 ppm, quintile IV was contaminated for a duration of only 4 s for pit-safety fan locations (1,1) and (1,3) for Qr30; quintile IV was clear of contamination when C_0 = 100 ppm for all other pit-safety fan locations and Q_{\text{ratios}}. When C_0 = 500 ppm, the duration of contamination for pit-safety fan locations (1,1) and (2,1) increased as Q_{\text{ratio}} decreased (pit-safety fan flow rate increased).
Figure 7.46. Duration of time in quintile IV when C(H$_2$S) $\geq$ 50 ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, with $C_0$ = 50, 100, and 500 ppm inside the manure pit.

Note: Error bars show $\pm$10% of the value of each bar.
Figure 7.47 shows the duration of time the barn airspace was contaminated in quintile V during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with initial H_2S concentrations of 50, 100, and 500 ppm inside the manure pit. Quintile V was clear of contamination for all pit-safety fan locations and Q_{ratio} when the initial manure pit concentration was 50 ppm. When C_0 = 100 ppm, all pit-safety fan locations resulted in a duration of contamination in quintile V of 80 s for Qr120; the duration of contamination for all other pit-safety fan locations for Qr30 and 60 were within ±10% of the case with no pit fan except for pit-safety fan location (2,2) with Qr30, which resulted in a duration of contamination in quintile V of 100 s. When C_0 = 500 ppm, the duration of contamination increased as Q_{ratio} decreased (pit-safety fan flow rate increased) for pit-safety fan locations (1,1), (2,1), and (2,2); the duration decreased as Q_{ratio} decreased for location (2,3); but there was no clear trend for location (1,3).
Figure 7.47. Duration of time in quintile V when $\text{C(H}_2\text{S)} \geq 50$ ppm during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, with $C_0 = 50$, 100, and 500 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
7.4.3 Maximum H$_2$S concentration in the barn during pit and barn ventilation

Figure 7.48, Figure 7.49, and Figure 7.50 show the maximum H$_2$S concentration in the barn overall and within each quintile for all pit-safety fan locations for Qr30, 60, and 120, respectively, for an initial H$_2$S concentration of 100 ppm inside the manure pit. These graphs are identical for all initial manure pit H$_2$S concentrations simulated. The maximum concentration axis can be interpreted as the percentage of initial manure pit concentration, i.e. the overall maximum concentration in the barn for all fan locations was 100 ppm, or 100% of the initial concentration value $C_0 = 100$ ppm. It is clear from the graphs that pit-safety fan location and Q$_{ratio}$ did not have a large impact on the maximum concentration in quintiles I, II, and V of the cross-ventilated barn airspace during pit-safety ventilation, where the maximum concentration reached was within ±10% of the initial concentration. The only factor that affected the maximum concentration in those barn quintiles was the initial manure pit H$_2$S gas concentration. However, there are some visible differences between Q$_{ratio}$ in quintiles III and IV.

The maximum concentration in quintile III increased as Q$_{ratio}$ decreased (pit-safety fan flow rate increased) for pit-safety fan locations (2,2) and (2,3). The maximum concentration in quintile IV was within ±10% (the error bars overlap) between Qr60 and 120 (Figure 7.49 and Figure 7.50, respectively), but for Qr30 the maximum concentration increased for all pit-safety fan locations, with the largest difference for fan locations (1,1) and (1,3) (Figure 7.48).
Figure 7.48. Maximum H$_2$S concentration in the barn airspace during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30 and C$_0$ = 100 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.49. Maximum H$_2$S concentration in the barn airspace during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr60 and $C_0 = 100$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.50. Maximum H$_2$S concentration in the barn airspace during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr120 and C$_0$ = 100 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.51 shows the maximum concentration in barn quintile I during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with an initial H₂S concentration of 100 ppm inside the manure pit. The maximum concentration in quintile I was 100% of the initial manure pit concentration for all fan locations and Q\textsubscript{ratio}s, including the case with no pit fan.

![Diagram showing maximum H₂S concentration in barn quintile I](image)

Figure 7.51. Maximum H₂S concentration in barn Quintile I during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, and C\textsubscript{0} = 100 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.52 shows the maximum concentration in barn quintile II during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with an initial H$_2$S concentration of 100 ppm inside the manure pit. The maximum concentration in quintile II ranged from 94% to 100% of the initial manure pit concentration for all fan locations and Q$_{ratios}$, including the case with no pit fan.

Figure 7.52. Maximum H$_2$S concentration in barn Quintile II during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, and C$_0$ = 100 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.53 shows the maximum concentration in barn quintile III during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with an initial H$_2$S concentration of 100 ppm inside the manure pit. There do not appear to be large differences or clear trends in maximum concentration versus Q$_{ratio}$ for pit-safety fan locations (1,1), (1,3), and (2,1). However, for fan locations (2,2) and (2,3) the maximum concentration in quintile III increased as Q$_{ratio}$ decreased (pit-safety fan flow rate increased).
Figure 7.53. Maximum H$_2$S concentration in barn Quintile III during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, and $C_0 = 100$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.54 shows the maximum concentration in barn Quintile IV during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with an initial H$_2$S concentration of 100 ppm inside the manure pit. There do not appear to be large differences or clear trends in maximum concentration versus $Q_{ratio}$ for pit-safety fan locations (2,1), (2,2), and (2,3). However, for fan locations (1,1) and (1,3) the maximum concentration in quintile III was more than 10% greater for Qr30 than Qr60 or 120.

Figure 7.54. Maximum H$_2$S concentration in barn Quintile IV during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, and $C_0 = 100$ ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
Figure 7.55 shows the maximum concentration in barn quintile V during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120 with an initial H$_2$S concentration of 100 ppm inside the manure pit. The maximum concentration in quintile V was 98% of the initial manure pit concentration for all fan locations and Q$_{ratio}$, including the case with no pit fan.

Figure 7.55. Maximum H$_2$S concentration in barn Quintile V during pit-safety ventilation for all CV simulation case pit-safety fan locations for Qr30, 60, and 120, and C$_0$ = 100 ppm inside the manure pit.

Note: Error bars show ±10% of the value of each bar.
7.4.4 $T_{pel}$ versus $Q_{ratio}$

This section compares the simulated $T_{pel}$ times for the CV cases (pit-safety fan locations and $Q_{ratio}$) to the case with no pit fan. Figure 7.56 shows the duration of ventilation required to reach a maximum $H_2S$ concentration of 10 ppm ($T_{pel}(10)$) everywhere inside the manure pit from an initial $H_2S$ concentration of 100 ppm for all CV simulation cases. It is clear from the graph that all CV simulation case pit-safety fan locations and $Q_{ratio}$ resulted in less time to reach $T_{pel}(10)$ inside the manure pit than the case with no pit fan. At pit-safety fan location (1,1), it appears that as $Q_{ratio}$ decreased (pit-safety fan flow rate increased), $T_{pel}(10)$ decreased. At locations (1,3), (2,1), (2,2), and (2,3), $Q_{r120}$ required the longest duration of time to reach $T_{pel}(10)$. $Q_{r60}$ reached $T_{pel}(10)$ in less time than $Q_{r30}$ for those locations, but only the case with pit-safety fan location (2,1) had a difference greater than 10%.

Figure 7.57 shows the duration of ventilation required to reach a maximum $H_2S$ concentration of 1 ppm ($T_{pel}(1)$) everywhere inside the manure pit from an initial $H_2S$ concentration of 100 ppm for all CV simulation cases. Trends are similar to those seen in Figure 7.56, except at location (2,1) where $Q_{r60}$ required slightly more time than $Q_{r30}$ to reach $T_{pel}(1)$. In general, cases with pit-safety fan locations closer to the cross-ventilated barn exhaust fans required longer durations of time to reach $T_{pel}(10)$ and $T_{pel}(1)$ inside the manure pit for all $Q_{ratios}$. There were two exceptions, but the $T_{pel}$ times were less than 10% different. The first exception was for $Q_{r60}$, where the case with pit-safety fan location (2,2) required slightly more time to reach $T_{pel}(10)$ than location (2,1). The second exception was for $Q_{r120}$, where the case with pit-safety fan location (2,3) required slightly more time to reach $T_{pel}(1)$ than that for location (2,2). Overall, cases with pit-safety fan locations (1,1) and (1,3) required the most time to reach $T_{pel}(10)$ and $T_{pel}(1)$ for all $Q_{ratios}$, and the pit-safety fan location (2,3) case required the shortest duration of time.
Figure 7.56. $T_{pe1}(10)$ vs. $Q_{ratio}$ for CV simulation cases with $C_0 = 100$ppm.

Note: Error bars show ±10% of the value of each bar.
Figure 7.57. $T_{pel}(1)$ vs. $Q_{ratio}$ for CV simulation cases with $C_0 = 100$ppm.

Note: Error bars show ±10% of the value of each bar.
7.4.5 Predicting initial concentration that results in C(H₂S) ≥ 50 ppm in each quintile

The maximum concentration on the measurement plane located 0.15 m (6 in.) above the slotted floor in each barn quintile is a linear function of initial manure pit concentration. This means for each pit-safety fan location and flow rate it is possible to predict the initial concentration that will result in C(H₂S) ≥ 50 ppm in each barn quintile. The maximum concentration on the measurement plane anywhere in the barn is simply equal to the largest maximum value in any quintile.

Using the $C_0$ scaling method from Chapter 5, the maximum concentration in each barn quintile can be predicted from the maximum concentration when $C_0 = 100$ ppm. For example, the cross-ventilated No Pit Fan case had maximum H₂S concentrations of 98 ppm, 34 ppm, 45 ppm, 94 ppm, and 100 ppm in barn quintiles V, IV, III, II, and I, respectively, when the initial manure pit H₂S concentration was 100 ppm. Scaling each maximum value by $C_0$ shows that the maximum concentrations in barn quintiles V, IV, III, II, and I were 98%, 34%, 45%, 94%, and 100%, respectively, of the initial concentration in the manure pit. Dividing the barn contamination threshold value of 50 ppm by these percentages yields the initial manure pit concentration that will result in C(H₂S) ≥ 50 ppm in each quintile of the barn:

\[
\begin{align*}
50 \text{ ppm} / 0.98 &= 51 \text{ ppm for Quintile V} \\
50 \text{ ppm} / 0.34 &= 147 \text{ ppm for Quintile IV} \\
50 \text{ ppm} / 0.45 &= 111 \text{ ppm for Quintile III} \\
50 \text{ ppm} / 0.94 &= 53 \text{ ppm for Quintile II} \\
50 \text{ ppm} / 1.00 &= 50 \text{ ppm for Quintile I}
\end{align*}
\]

Table 7.20 lists the initial manure pit H₂S concentration that results in C(H₂S) ≥ 50 ppm in each barn quintile for each CV simulation case and $Q_{\text{ratio}}$. 

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Table 7.20. Initial manure pit \(\text{H}_2\text{S}\) concentration (ppm) that results in \(\text{C(\text{H}_2\text{S})} \geq 50\) ppm in each quintile during pit-safety ventilation for cross-ventilated barn simulation cases.

<table>
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7.4.6 Keeping animals in cross-ventilated barns during pit-safety ventilation

Ultimately, the decision to remove animals from the barn during manure pit-safety ventilation events will be up to the facility owner. This discussion is framed in the context of the OSHA regulation that allows a maximum human exposure level of 50 ppm for a duration up to 10 minutes based on the assumption that no prior exposure has occurred during the day. This discussion may not be valid for stricter exposure limits such as those specified by NIOSH or ACGIH, but the procedures used to analyze the simulation results for an \(\text{H}_2\text{S}\) gas exposure limit of 50 ppm can be applied to other threshold values. There are no established safe exposure limits to \(\text{H}_2\text{S}\) gas for animals in confinement housing.
Confinement of animals within certain areas of a barn will depend on the initial H$_2$S gas concentration inside the manure pit, the pen layout or availability of temporary pen dividers, and the number of animals that can safely be kept in the reduced pen area for a short duration of time. Cases CV21 Qr120, CV22 Qr60, CV23 for $Q_{\text{ratios}}$ 60 and 120, and the case with no pit fan resulted in contiguous clear areas where $C(\text{H}_2\text{S}) \leq 50$ ppm when the initial concentration in the manure pit was 300 ppm or lower. All other pit-safety fan locations and $Q_{\text{ratios}}$ fan resulted in contiguous clear areas when the initial H$_2$S gas concentration inside the manure pit was 200 ppm or lower.

For all CV simulation case pit-safety fan locations and $Q_{\text{ratios}}$, the maximum concentration in quintile I was equal to the initial H$_2$S concentration inside the manure pit, and the maximum concentration in quintiles II and V was within ±10% of the initial concentration. These quintiles had greater than 70% clear area when $C_0 = 50$ ppm, less than 50% clear area when $C_0 = 100$ ppm, and were completely contaminated when $C_0 = 500$ ppm. Therefore, animals should be removed from at least portions of quintiles I, II, and V of mechanically cross-ventilated barns (as configured in this study) when $C_0 \geq 50$ ppm. Quintiles III and IV were completely clear for all pit-safety fan locations and $Q_{\text{ratios}}$ when $C_0 = 50$ ppm and had 99% or greater clear area when $C_0 \leq 100$ ppm, which means at least 40% of contiguous overall barn area was available for relocation of animals during safety pit-safety ventilation. When $51 \leq C_0 \leq 55$ ppm, 72% to 97% of contiguous barn area had $C(\text{H}_2\text{S}) \leq 50$ ppm. When $75 \leq C_0 \leq 100$ ppm, 45% to 61% of contiguous barn area had $C(\text{H}_2\text{S}) \leq 50$ ppm. When $C_0 = 200$ ppm, 31% to 39% of contiguous barn area had $C(\text{H}_2\text{S}) \leq 50$ ppm. When $C_0 = 300$ ppm, 27% to 33% of contiguous barn area had $C(\text{H}_2\text{S}) \leq 50$ ppm. However, when $C_0 \geq 400$ ppm, less than 19% of the barn area had $C(\text{H}_2\text{S}) \leq 50$ ppm, and the area was not contiguous.
7.4.7 Hypothesis discussion

The results from the CV simulation cases are discussed in this section in the context of the research hypotheses from Chapter 2. When the hypotheses were first drafted, it was thought that careful selection of pit-safety ventilation fan location and flow rate might be able to prevent contamination of the barn airspace during manure pit and barn ventilation events. However, the simulation results show that contamination of the barn airspace occurs even when no pit-safety fan is used. The hypotheses are restated here for clarity.

\[ H_0: \text{For a given initial concentration of } H_2S \text{ gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate (m}^3/\text{s}), there is no positive pressure pit-safety ventilation air flow rate (m}^3/\text{s}) \text{ that will result in dangerous conditions (C(H}_2S) \geq 50 \text{ ppm for 10 min) in selected contiguous barn areas when the initial pit concentration is greater than 50 ppm.} \]

For null hypothesis (H\textsubscript{0}) testing, the rejection region is everything outside the graph of C(H\textsubscript{2}S) > 50 ppm for 10 minutes. So, for discussion purposes, if barn quintiles had C(H\textsubscript{2}S) \leq 50 ppm during pit-safety ventilation, then we must reject H\textsubscript{0}. The “10 minute” criterion did not need to be considered when discussing H\textsubscript{0} below because the quintiles that had durations of contamination for the full 300 s of pit-safety ventilation also had maximum concentrations greater than 50 ppm and therefore fell outside the rejection region. Another region that might be considered is the OSHA ceiling limit of 20 ppm for 8 hours, but few of the simulation cases had quintiles where C(H\textsubscript{2}S) < 20 ppm when the initial manure pit H\textsubscript{2}S gas concentration was 50 ppm or greater, and the concentration in all of those cases would have decayed to zero in far less than 8 hours.
1. For all CV pit-safety fan locations and \( Q_{\text{ratios}} \) and the case with no pit fan, all quintiles had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) during pit-safety ventilation when the initial \( \text{H}_2\text{S} \) gas concentration inside the manure pit was 50 ppm. The duration of time when \( C(\text{H}_2\text{S}) = 50 \text{ ppm} \) was 130 seconds or less for all cases in quintile I, and only 30 seconds in quintile II for case CV22 Qr30. The \( \text{H}_2\text{S} \) concentration in quintiles III, IV, and V never reached 50 ppm.

2. For nearly all CV pit-safety fan locations and \( Q_{\text{ratios}} \) and the case with no pit fan, quintiles II, III, IV, and V had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) during safety pit-safety ventilation when the initial \( \text{H}_2\text{S} \) gas concentration inside the manure pit was 51 ppm, but \( H_0 \) should be rejected for quintile I because the maximum concentration was 51 ppm. There were exceptions for case CV22 Qr30 and case CV23 for \( Q_{\text{ratios}} \) 30 and 60, which resulted in a maximum concentration of 51 ppm in quintile II for a duration of 90 seconds or less. The duration of time when \( C(\text{H}_2\text{S}) \geq 50 \text{ ppm} \) was 190 seconds or less in quintile I, 90 seconds or less in quintile II, and 15 seconds or less in quintile V.

3. For nearly all CV pit-safety fan locations and \( Q_{\text{ratios}} \) and the case with no pit fan, quintiles III and IV had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) during safety pit-safety ventilation when the initial \( \text{H}_2\text{S} \) gas concentration inside the manure pit was 55 ppm, but \( H_0 \) should be rejected for quintiles I, II, and V because the maximum concentration in those quintiles was greater than 50 ppm. One exception was for case CV22 Qr30 which resulted in a maximum concentration of 52 ppm in quintile III for a duration of 40 seconds. The duration of time when \( C(\text{H}_2\text{S}) \geq 50 \text{ ppm} \) was 270 seconds or less in quintile I, 140 seconds or less in quintile II, and 47 seconds or less in quintile V.

4. For nearly all CV pit-safety fan locations and \( Q_{\text{ratios}} \) and the case with no pit fan, quintiles III and IV had \( C(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) during safety pit-safety ventilation when the initial \( \text{H}_2\text{S} \) gas concentration inside the manure pit was 75 ppm, but \( H_0 \) should be rejected for quintiles I, II, and V because the maximum concentration in those quintiles was greater than 50 ppm. There were exceptions for \( Q_{\text{ratios}} \) 30 and 60 for cases CV22 and CV23.
which resulted in maximum concentrations greater than 50 ppm in quintile III for up to 90 seconds. The duration of time when $C(H_2S) \geq 50$ ppm was 290 seconds or less in quintile I, 224 seconds or less in quintile II, and 70 seconds or less in quintile V.

5. For the majority of CV pit-safety fan locations and $Q_{ratio}$ and the case with no pit fan, quintiles III and IV had $C(H_2S) \leq 50$ ppm during safety pit-safety ventilation when the initial $H_2S$ gas concentration inside the manure pit was 100 ppm, but $H_0$ should be rejected for quintiles I, II, and V because the maximum concentration in those quintiles was greater than 50 ppm. There were exceptions for $Q_{ratio}$ 30 for cases CV11 and CV13, which resulted in maximum concentrations greater than 50 ppm in quintile IV for a duration of 4 seconds. Other exceptions were for $Q_{ratio}$ 30 and 60 for case CV22, and all $Q_{ratio}$ for case CV23 which resulted in maximum concentrations greater than 50 ppm in quintile III for up to 120 seconds. The duration of time when $C(H_2S) \geq 50$ ppm was 290 seconds or less in quintile I, 224 seconds or less in quintile II, and 70 seconds or less in quintile V.

6. For all CV pit-safety fan locations and $Q_{ratio}$ and the case with no pit fan, there were no quintiles where $C(H_2S) \leq 50$ ppm during pit-safety ventilation when the initial manure pit $H_2S$ gas concentration was 200 ppm or greater.
**H₁**: For a given initial concentration of \( \text{H}_2\text{S} \) gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate (\( \text{m}^3/\text{s} \)), there exists a maximum pit air ventilation flow rate (\( \text{m}^3/\text{s} \)) that can be used without raising the concentration of \( \text{H}_2\text{S} \) gas in selected contiguous barn areas (measured at 0.15 m (6 in.) above the floor) above a threshold level of 50 ppm (\( \text{C}^*(\text{H}_2\text{S}) \geq 50 \text{ ppm for 10 min} \)), yet will evacuate the gas inside the pit within 30 minutes.

**H₂**: For a given initial concentration of \( \text{H}_2\text{S} \) gas (ppm) inside a confined-space manure pit and a fixed level of barn ventilation air flow rate (\( \text{m}^3/\text{s} \)), there exists a minimum effective pit-safety ventilation air flow rate (\( \text{m}^3/\text{s} \)) that will result in \( T_{\text{pel}}(10 \text{ ppm}) \) being reached in a defined acceptable maximum amount of time (30 minutes, or another preselected reasonable time limit) without creating dangerous conditions (\( \text{C}^*(\text{H}_2\text{S}) \geq 50 \text{ ppm for 10 min} \)) in selected contiguous barn areas (measured at 0.15 m (6 in.) above the floor).

Alternate hypotheses \( \text{H}_1 \) and \( \text{H}_2 \) deal with reaching \( T_{\text{pel}} \) inside the manure pit within 30 minutes for cases that resulted in quintiles where \( \text{C}^*(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) inside the barn during pit-safety ventilation and \( \text{H}_0 \) was rejected. So, for discussion purposes, if quintiles had \( \text{C}^*(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) during pit-safety ventilation and \( \text{H}_0 \) was rejected, we must only reject \( \text{H}_1 \) or \( \text{H}_2 \) if \( T_{\text{pel}} > 30 \) minutes.

1. For all pit CV fan locations and \( Q_{\text{ratio}} \), and the case with no pit fan, \( T_{\text{pel}}(10 \text{ ppm}) \) was reached in less than 30 minutes when the initial manure pit \( \text{H}_2\text{S} \) gas concentration was 100 ppm or lower. The case with no pit fan required longer than 30 minutes to reach \( T_{\text{pel}}(10 \text{ ppm}) \) when \( C_0 \geq 200 \text{ ppm} \), and case CV11 \( Q_{\text{ratio}}120 \) required longer than 30 minutes to reach \( T_{\text{pel}}(10 \text{ ppm}) \) when \( C_0 = 500 \text{ ppm} \). However, there were no areas where \( \text{C}^*(\text{H}_2\text{S}) \leq 50 \text{ ppm} \) within the barn when the initial manure pit \( \text{H}_2\text{S} \) concentration was 200 ppm or greater, so we cannot evaluate \( \text{H}_1 \) or \( \text{H}_2 \) for those cases.
2. \( T_{pel}(1 \text{ ppm}) \) was only evaluated for CV cases for \( C_0 \leq 100 \text{ ppm} \), but it is reasonable to conclude that if \( T_{pel}(1 \text{ ppm}) \) required longer than 30 minutes to reach when \( C_0 \leq 100 \text{ ppm} \), it would also require longer than 30 minutes when \( C_0 \geq 100 \text{ ppm} \). The only cases that required longer than 30 minutes to reach \( T_{pel}(1 \text{ ppm}) \) were CV11 Qr120 and the case with no pit fan. Therefore, we must reject both \( H_1 \) and \( H_2 \) for cases CV11 Qr120 and the case with no pit fan because \( T_{pel}(1 \text{ ppm}) \) always required longer than 30 minutes to reach inside the manure pit when \( C_0 \geq 50 \text{ ppm} \).

7.5 Conclusions for cross-ventilated barn simulations

The purpose of this chapter was to identify zones within mechanically cross-ventilated barns with fully-slotted floors located above full-sized mechanically-ventilated manure pits that must be evacuated for ratios of \( Q_{pit}/Q_{barn} \) that result from pit gases being exhausted into the barn airspace. A series of CFD simulations was performed with different pit-safety ventilation fan locations and flow rates to investigate how these factors affect the area and duration of time when the barn airspace is contaminated with \( C(H_2S) \geq 50 \text{ ppm} \) and the maximum \( H_2S \) concentration on the barn measurement plane during pit and barn ventilation. The conclusions stated in this section are only valid for the specific mechanically cross-ventilated barn configuration, manure pit-safety fan locations and \( Q_{ratio} \), and initial manure pit \( H_2S \) concentrations used in this study.

7.5.1 Conclusions

1. Manure pit-safety fan location, \( Q_{ratio} \), and initial \( H_2S \) concentration in the manure pit influence the contaminated barn area, duration of contamination, maximum concentration in the barn airspace, and the duration of time required to reach \( T_{pel} \) in the manure pit for mechanically cross-ventilated barns during manure pit-safety ventilation.
2. There were large, contiguous areas in the barn that were not contaminated during manure pit-safety ventilation across nearly all fan locations and $Q_{\text{ratios}}$ when the initial manure pit $H_2S$ gas concentration was 100 ppm or lower.

3. The maximum concentration in the barn airspace in cross-ventilated barns during pit-safety ventilation was within ±10% of the initial manure pit $H_2S$ concentration in quintiles I, II, and V for all fan locations and $Q_{\text{ratios}}$, therefore animals should be evacuated from at least portions of quintiles I, II, and V of mechanically cross-ventilated barns when $C_0 \geq 50$ ppm.

4. When $51 \leq C_0 \leq 55$ ppm, 72% to 97% of contiguous barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratios}}$.

5. When $75 \leq C_0 \leq 100$ ppm, 45% to 61% of contiguous barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratios}}$.

6. When $C_0 = 200$ ppm, 31% to 39% of contiguous barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratios}}$.

7. When $C_0 = 300$ ppm, 27% to 33% of the barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratios}}$, but the area was not contiguous for most cases.

8. When $C_0 \geq 400$ ppm, less than 19% of the barn area had $C(H_2S) \leq 50$ ppm across all pit-safety fan locations and $Q_{\text{ratios}}$, and the area was not contiguous.

9. All pit-safety fan locations and $Q_{\text{ratios}}$ resulted in shorter $T_{\text{pit}}$ times compared to the case with no pit fan.

10. The mechanically cross-ventilated barns simulated in this study had large contiguous clear areas in quintiles III and IV for all pit-safety fan locations and $Q_{\text{ratios}}$ and the case with no pit fan when the initial manure pit $H_2S$ concentration was 200 ppm or lower.
Chapter 8

Summary, Conclusions, and Recommendations for Future Work

This chapter summarizes the conclusions for the CFD model development and validation (Chapter 4), the $C_0$ scaling method (Chapter 5), and TV and CV barn simulations (Chapter 6 and Chapter 7, respectively). A design methodology for engineers to use when designing or evaluating manure pit-safety ventilation systems is described, and recommendations are provided for revision of the animal evacuation provisions of ANSI/ASABE Standard S607. A list of recommendations for future work is provided at the end of this chapter.

8.1 Summary

The overall goal of this study was to develop methodologies and protocols for evaluating barn air contamination hazards during positive pressure pit-safety ventilation and to demonstrate that manure pit ventilation configuration and fan capacity do influence the level of air contamination hazard in the barn. An experiment was performed to measure $H_2S$ gas concentration at several locations in a swine nursery room during manure pit and barn ventilation. A CFD model and simulation protocols were developed to predict the distribution of $H_2S$ gas through the pit and nursery room airspace during ventilation, and CFD simulation results were compared to the measured data to validate the CFD model and demonstrate that SolidWorks Flow Simulation (SWFS) is suitable for research use. A $C_0$ scaling method was developed based on observed trends that can be used to extend the information obtained from one CFD simulation for a certain uniform initial manure pit $H_2S$ concentration to a wide range of different initial concentrations. Finally, parametric studies were performed for tunnel ventilated and mechanically cross-ventilated barns that investigated the effect of pit-safety ventilation fan
location and flow rate on the formation of contaminated zones within the barn that must be evacuated due to H₂S gas from the pit being exhausted into the barn airspace.

8.1.1 CFD model development and validation

A CFD model of a swine nursery room was developed, and simulation results were compared to gas concentration measurements from a ventilation experiment. The best performing gas distribution case, described in Section 4.4.5, used a variable initial concentration based on average measured initial concentrations at each meter location inside the manure pit. When comparing simulated to measured gas concentration curves during manure pit and nursery room ventilation for the best performing case, 6 out of 15 meters met statistical validation criteria without any further processing.

The gas meters used during the nursery room experiment contain electrochemical sensors that exhibit first-order response behavior to step changes in gas concentration. Further analysis of meter locations where validation criteria were not met revealed measurement errors typical of a first-order system response. This included time lag and differences in magnitude between simulated and measured curves. By making reasonable shifts to better align the simulated and measured curves in time, the statistical validation criteria improved for two meters located above the slotted floor, and further improvements were attained by applying a first-order instrument response transformation to the simulated concentration curves. This strongly suggests that simulations performed using SWFS are adequate for research purposes, and the CFD simulations have been validated by the measured data.

8.1.2 C₀ scaling method

A trend observed during analysis of CFD simulation results for a given pit and barn shape and ventilation configuration (the same pit-safety fan location and flow rate with the same barn
ventilation rate) with different initial manure pit H\textsubscript{2}S gas concentrations suggested that the ratio of concentration at each time step during ventilation was equal to the ratio between the initial concentrations inside the manure pit. This relationship was explored using the simulation results from the nursery room initial concentration bracketing study described in Section 4.4.5. It was determined that C/C\textsubscript{0} scaling could be used to expand the results from one CFD simulation at one C\textsubscript{0} value to a wide range of C\textsubscript{0} values. The maximum error when comparing simulated to estimated C/C\textsubscript{0} values was ± 2.5% for the global maximum H\textsubscript{2}S gas concentration over time. For practical purposes, a safe C\textsubscript{0} limit of 500 ppm was selected for estimation purposes. With an error level of ± 2.5%, the estimation uncertainty would be ± 12.5 ppm when the simulated initial H\textsubscript{2}S concentration is 500 ppm.

8.1.3 Tunnel ventilated barn simulations

Simulations were performed for a 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long) tunnel ventilated (TV) barn located above a full-sized manure pit with a fully-slotted cover. Manure pit-safety ventilation fan configuration (location and flow rate) was varied to simulate the resulting distribution of H\textsubscript{2}S gas in the barn airspace during a barn and manure pit-safety ventilation event. Simulation results for each pit-safety fan configuration were analyzed to determine the affected area in the barn and the duration of time when the concentration of H\textsubscript{2}S gas was 50 ppm or greater, the maximum H\textsubscript{2}S concentration in the barn airspace, and how much time was required to reach T\textsubscript{pel} in the manure pit. The maximum concentration in the barn airspace in tunnel ventilated barns during pit-safety ventilation was equal to the initial manure pit H\textsubscript{2}S concentration in quintile V (the transverse quintile located nearest the exhaust fan end of the barn) for all fan locations and Q\textsubscript{ratios}, therefore animals should always be evacuated from quintile V of tunnel ventilated barns when C\textsubscript{0} ≥ 50 ppm. In general, counterflow pit-safety fan locations resulted in longer T\textsubscript{pel} times, and parallel flow pit-safety fan locations resulted in shorter T\textsubscript{pel} times.
than the case with no pit fan. Parallel flow with the pit-safety fan located along the longitudinal centerline of the barn resulted in less overall contaminated area in the barn than all other cases as well as the case with no pit fan.

8.1.4 Cross-ventilated barn simulations

Simulations were performed for a 12.20 m wide × 30.49 m long (40 ft wide × 100 ft long) mechanically cross-ventilated (CV) barn located above a full-sized manure pit with a fully-slotted cover. Manure pit-safety ventilation fan configuration (location and flow rate) was varied to simulate the resulting distribution of H\textsubscript{2}S gas in the barn airspace during a barn and manure pit-safety ventilation event. Simulation results for each pit-safety fan configuration were analyzed to determine the affected area in the barn and the duration of time when the concentration of H\textsubscript{2}S gas was 50 ppm or greater, the maximum H\textsubscript{2}S concentration in the barn airspace, and how much time was required to reach T\textsubscript{pel} in the manure pit. The maximum concentration in the barn airspace in cross-ventilated barns during pit-safety ventilation was within ±10% of the initial manure pit H\textsubscript{2}S concentration in quintiles I, II, and V for all fan locations and Q\textsubscript{ratios}, therefore animals should always be evacuated from quintiles I, II, and V of mechanically cross-ventilated barns when C\textsubscript{0} ≥ 50 ppm. However, there were large contiguous clear areas in quintiles III and IV for all simulated cases when the initial manure pit H\textsubscript{2}S concentration was 200 ppm or lower. All pit-safety fan locations and Q\textsubscript{ratios} resulted in shorter T\textsubscript{pel} times than the case with no pit fan.

8.1.5 The developed methodology

The fourth objective of this research was to develop a methodology that engineers can use when designing and evaluating manure pit-safety ventilation systems that reduce the risk of creating hazardous conditions inside the barn during pit-safety ventilation. The developed methodology is a combination of developing a validated CFD model (including how the different
boundary conditions were represented and the porous media used to represent the slotted floor),
the $C_0$ scaling method used to infer results for many different initial pit concentrations from one
simulation with $C_0 = 100$ ppm, and the data analysis methods used to determine which zones on
the measurement plane in the barn were contaminated for different fan locations, flow rates, and
initial manure pit gas concentrations. It is assumed that the user is already familiar with
configuring CFD models and determining appropriate grid and time step sizes. This section lists
specific design steps, followed by references to other relevant sections in this document.

1) Define the plane of interest in the barn. What height is most important? If the plane is
greater than 0.30 m (1 ft) above the floor, is it acceptable to have $H_2S$ gas below this height?
More than one plane could be used if multiple heights are important. See section 6.2.6.3 on
page 171.

2) Perform a simulated wind tunnel test at expected air flow rates if porous media will be used
to represent the slotted flooring. See sections 4.3.6 on page 87 and 6.2.6.7 on page 179.

3) Perform a “no pit fan” simulation for each barn flow rate to use as a baseline for comparisons
against various pit-safety fan locations and flow rate design cases. Continue the simulation
until the maximum concentration inside the manure pit is 1 ppm (or less).

4) Perform a CFD simulation for each design case using an initial pit concentration of 100 ppm.
Continue the simulation until the maximum concentration inside the manure pit is 1 ppm (or
less).

5) Extract point values on the plane(s) of interest from the simulation results.

6) Multiply the results by 2,3,4,5 to calculate the results of $C_0$ values of 200, 300, 400, and 500
ppm (or by lower ratios of $C/C_0$ if desired).

7) Create a composite map of contaminated area on the plane of interest. See section 6.3.3 on
page 191.
8.2 Recommended revisions to ASABE S607

The final objective of this study was to provide recommendations for revision of the animal evacuation provisions of ASABE Standard S607 (approved as an ASABE Standard October 2010; approved as an American National Standard November 2010). Based on results from the TV and CV barn simulations, the following revisions are recommended:

1) The TV and CV “No Pit Fan” simulation cases showed that it may be possible for hazardous gases from the manure pit to enter the barn airspace even without a pit-safety ventilation fan. This reinforces the recommendation that a manure pit should never be ventilated without also operating the barn ventilation system. S607 currently recommends that the barn exhaust fans be operated at the hot weather maximum ventilation rate for five minutes before ventilating the manure pit, as well as for the entire duration of the pit-safety ventilation event. S607 could be updated to recommend operating the barn exhaust fans for longer than five minutes, while acknowledging this could lower barn temperatures during cold weather.

2) All of the simulation cases performed for this study had uniform initial conditions inside the manure pit. In reality, it is more likely that the initial gas distribution inside the manure pit would be non-uniform. The initial manure pit concentration should be measured at multiple locations prior to the start of pit-safety ventilation. Continuous gas monitoring should be performed at more than one location in the barn and animal occupants should be observed for signs of distress during manure pit and barn ventilation.

3) ASABE Standard S607 states that animals and personnel must be removed when the concentration of H₂S gas inside the manure pit is 80 ppm or greater (ASABE, 2017b). However, the OSHA standard 29 CFR 1910.1000 for safe exposure to H₂S for humans stipulates that if no previous exposure has occurred, a worker may be exposed to a maximum concentration of 50 ppm for a duration of 10 minutes (Occupational Safety & Health Administration, 1997). Therefore, the S607 standard should be updated to recommend
removal of personnel from the animal living space during pit-safety ventilation events whenever the initial manure pit concentration is 50 ppm or greater. However, if engineering analyses similar to those presented in this dissertation demonstrate that contiguous portions of the barn are not contaminated during manure pit-safety ventilation, those portions of the barn may not need to be evacuated.

8.3 Conclusions

1. SWFS is suitable for research use for simulation of tunnel and mechanically cross-ventilated barns located above full-sized manure pits with fully slotted covers.

2. The initial H$_2$S gas distribution inside the manure pit has a substantial impact on the gas distribution and concentration levels in the barn airspace during combined pit and barn ventilation.

3. First-order gas monitoring instruments can be successfully modeled in CFD simulations by transforming the transient measurements.

4. C/C$_0$ scaling can be used to estimate contaminated area, maximum concentration, and duration of time required to reach T$_{pel}$ for a wide range of uniform initial manure pit concentrations for a given barn and manure pit-safety ventilation configuration by running a single CFD simulation.

5. Manure pit-safety fan location, Q$_{ratio}$, and initial H$_2$S concentration in the manure pit have an influence on the contaminated barn area, duration of contamination, maximum concentration in the barn airspace, and duration of time required to reach T$_{pel}$ in the manure pit for tunnel ventilated and mechanically cross-ventilated barns during manure pit-safety ventilation.

6. For the same barn and pit dimensions, Q$_{ratio}$, and initial manure pit H$_2$S concentrations, barn ventilation scheme has a large impact on contaminated area and duration inside the
barn during pit-safety ventilation. The duration of contamination for TV barns was relatively short compared to CV barns for the same initial manure pit concentrations and $Q_{\text{ratios}}$.

7. Portions of tunnel ventilated and mechanically cross-ventilated barns must be evacuated during manure pit-safety ventilation when $C_0 \geq 50$ ppm.

8. When the initial manure pit H$_2$S gas concentration ($C_0$) was 100 ppm or less, at least 70% of contiguous area in tunnel ventilated barns had $C(H_2S) \leq 50$ ppm during manure pit-safety ventilation, and this percentage decreased as $C_0$ exceeded 100 ppm.

9. When the initial manure pit H$_2$S gas concentration ($C_0$) was 100 ppm or less, at least 45% of contiguous area in mechanically cross-ventilated barns had $C(H_2S) \leq 50$ ppm during manure pit-safety ventilation, and this percentage decreased as $C_0$ exceeded 100 ppm.

10. The methodology used in this research can be applied by engineers to design manure pit-safety ventilation systems that reduce the risk of creating, or reduce the spatial extent of hazardous conditions inside the barn during pit-safety ventilation.

**8.4 Recommendations for future work**

This study was performed for a specific barn size located above a full-sized manure pit with a fully-slotted cover and two barn ventilation configurations, and the initial H$_2$S gas concentration inside the manure pit was assumed to be uniform.

1. Other barn sizes, pit sizes, cover types, and ventilation configurations may result in clear zones large enough to safely relocate animals temporarily during pit and barn ventilation events. More work is needed to extend the results of this study to other barn sizes and configurations and other ventilation configurations.

2. Non-uniform initial manure pit H$_2$S concentrations were not included in the TV and CV simulation cases for this study. More work is needed to determine the effect of non-
uniform initial conditions inside the manure pit on contaminated areas in the barn airspace during pit and barn ventilation.

3. The $C_0$ scaling method developed was demonstrated to be valid for uniform initial manure pit $H_2S$ concentrations up to 500 ppm. Additional research is needed to determine the limitations of this method for non-uniform initial conditions inside the manure pit and for initial $H_2S$ concentrations greater than 500 ppm.

4. A first order sensor response was observed for the data collected during the experimental phase of this research study, and it was demonstrated that post-processing corrections could be applied to better match simulated transient gas concentration curves. More work is needed to develop real-time sensor response correction circuitry, or to develop new sensor technology with a quicker response time.

5. Further study is needed to evaluate zones of contamination and $T_{pe}$ times for barns located above pits with negative pressure pit ventilation schemes.

6. More research is needed to define the response of animals and humans to $H_2S$ levels between the short term maximum level of 50 ppm and the IDLH value of 100 ppm.

8.5 General manure pit safety recommendations

1. Farmers or personnel with manure pits should obtain and use gas detectors before performing pit-safety ventilation or entering manure pits.

2. Animals do not need to be removed from barns during pit-safety ventilation when the maximum initial $H_2S$ concentration inside the manure pit is less than 50 ppm.

3. In addition to designing ventilation systems that reduce the level of hazard in barns during pit-safety ventilation, safety may be improved for new construction by including more flexible pen or fencing designs (to allow animals to be moved to clear zones), or removal of manure from barns altogether (no underbarn storage).
REFERENCES


Appendix A

Cross-ventilated barn design calculations for swine

From MWPS-1 Section 510, the recommended space for 150-220 lb finishing pigs in enclosed housing is 8 ft$^2$/pig:

\[
\frac{40 \times 100 \text{ barn}}{8 \text{ ft}^2/\text{pig}} = 500 \text{ finishing pigs} \approx \text{will use 450 pigs for this design case}
\]

From MWPS-1 Table 633-2, the recommended hot weather ventilation rate is 120 cfm for each 150-220 lb finishing pig:

\[
450 \text{ pigs} \times 120 \frac{\text{cfm}}{\text{pig}} = 54,000 \text{ cfm} \approx \text{will use 60,000 cfm}
\]

J&D Manufacturing (http://www.jdmfg.com) builds a 50” diameter fan rated at 20,800 cfm @ 0.10 in. SP:

\[
\frac{60,000 \text{ cfm}}{20,800 \text{ cfm/fan}} = 3 \text{ fans}
\]

The inlet slot will be located just below the eaves on both sidewalls and will extend along the full length of the barn. The recommended inlet air velocity for cross-ventilated barns is 600 ft/min. The slot width was calculated from:
\[
\text{Inlet Slot Area} = \left( \frac{Q}{V} \right) = \left( \frac{60,000 \text{ cfm}}{600 \text{ ft/min}} \right) = 100.0 \text{ ft}^2 = 14,400 \text{ in}^2
\]

\[
\text{Inlet Slot Width} = \frac{\text{Area}}{\text{Length}} = \frac{14,400 \text{ in}^2}{2,400 \text{ in}} = 6.0 \text{ in}
\]
Appendix B

Phase I CFD simulation model settings

This section contains the SolidWorks Flow Simulation 2015 Project Settings used for the Nursery Room simulations from Phase I of this research project. Note: The Y and Z directions are switched in this list (i.e. Y was up in the actual simulation, however in this manuscript Z is used to denote the vertical direction).

INPUT DATA

Initial Mesh Settings
Automatic initial mesh: Off

Basic Mesh Dimensions
Number of cells in X: 102
Number of cells in Y: 32
Number of cells in Z: 40

Control Planes
Control planes in X direction
Name Minimum Maximum Number of cells Ratio
X1 -18.693 -18.198 2 1.000
X2 -18.198 0 50 1.000
X3 0 18.235 50 1.000

Control planes in Y direction
Name Minimum Maximum Number of cells Ratio
Y1 -2.010 -0.880 4 1.000
Y2 -0.880 0.250 4 1.000
Y3 0.250 3.492 10 1.000
Y4 3.492 8.010 14 1.000

Control planes in Z direction
Name Minimum Maximum Number of cells Ratio
Z1 -6.054 0 20 1.000
Z2 0 6.054 20 1.000

Solid/Fluid Interface
Small solid features refinement level: 2
Curvature refinement level: 0
Curvature refinement criterion: 0.505 rad
Tolerance refinement level: 2
Tolerance refinement criterion: 0.169 ft

Refining cells
Refine fluid cells: Off
Refine partial cells: Off
Refine solid cells: Off
Advanced narrow channel refinement: Off

Local Mesh Settings
Local Initial Mesh Pit-safety fan Inlet 1
Components: Face <1Pit-safety fan Inlet Split Line1>
Solid/fluid interface
  Small solid features refinement level: 0
  Curvature refinement level: 0
  Curvature refinement criterion: 0.555 rad
  Tolerance refinement level: 0
  Tolerance refinement criterion: 0.073 ft

Refining cells
  Refine all cells: On
  Level of refining all cells: 2

Narrow channels
  Advanced narrow channel refinement: On
  Characteristic number of cells across a narrow channel: 7
  Narrow channels refinement level: 5
  The minimum height of narrow channels: Off
  The maximum height of narrow channels: Off

Computational Domain

  Size
    X min: -18.693 ft
    X max: 18.235 ft
    Y min: -2.010 ft
    Y max: 8.010 ft
    Z min: -6.054 ft
    Z max: 6.054 ft

  Boundary Conditions
    2D plane flow: None
    At X min: Default
    At X max: Default
    At Y min: Default
    At Y max: Default
    At Z min: Default
    At Z max: Default

Physical Features
  Heat conduction in solids: Off
  Time dependent: On
  Gravitational effects: On
  Rotation: Off
  Flow type: Laminar and turbulent
  High Mach number flow: Off
  Humidity: Off
  Default roughness: 0 microinch

Gravitational Settings
  X component: 0 ft/s^2
  Y component: -32.19 ft/s^2
  Z component: 0 ft/s^2
  Default wall conditions: Adiabatic wall

Initial Conditions

  Thermodynamic parameters
    Static Pressure: 14.695947 lbf/in^2
    Temperature: 68.00 °F

  Velocity parameters
    Velocity vector
    Velocity in X direction: 0 ft/s
    Velocity in Y direction: 0 ft/s
Velocity in Z direction:  0 ft/s

Concentrations
   Substance fraction by volume
   Air  1000000.0000 ppm
   Hydrogen Sulfide  0 ppm

Turbulence parameters
   Turbulence energy and dissipation
   Energy:  0.000430 Btu/lb
   Dissipation:  0.33 lbf*ft/s/lb

Material Settings
   Fluids
   Air
   Hydrogen Sulfide

Boundary Conditions
   Outlet Velocity 1
      Type: Outlet Velocity
      Faces: Face<1>@Outlet Velocity Face
      Coordinate system: Face Coordinate System
      Reference axis:  X
   Flow parameters
      Flow vectors direction:  Normal to face
      Velocity normal to face:  18.920 ft/s

   Inlet Velocity 1
      Type: Inlet Velocity
      Faces: Face<2>@Pit-safety fan Inlet Split Linel
      Coordinate system: Face Coordinate System
      Reference axis:  X
   Flow parameters
      Flow vectors direction:  Normal to face
      Velocity normal to face:  20.060 ft/s
      Fully developed flow:  No
   Thermodynamic parameters
      Approximate pressure:  14.695947 lbf/in²
      Temperature:  68.00 °F

Concentrations
   Substance fraction by volume
   Air  1000000.0000 ppm
   Hydrogen Sulfide  0 ppm

Turbulence parameters
   Turbulence intensity and length
   Intensity:  5.00 %
   Length:  1.43 in

Boundary layer parameters
   Boundary layer type:  Turbulent

Ceiling Environment Pressure

442
Type: Environment Pressure
Faces: Face<3>@Boss-Extrude3
Coordinate system: Face Coordinate System
Reference axis: X

Thermodynamic parameters
Environment pressure: 14.695947 lbf/in^2
Temperature: 68.00 °F

Concentrations
Substance fraction by volume
Air
1000000.0000 ppm
Hydrogen Sulfide
0 ppm

Turbulence parameters
Turbulence energy and dissipation
Energy: 0.000430 Btu/lb
Dissipation: 0.33 lbf*ft/s/lb

Boundary layer parameters
Boundary layer type: Turbulent

Ideal Wall 1
Type: Ideal wall
Faces: Face<4>@Cut-Extrude1, Face<5>@Cut-Extrude1, Face<6>@Cut-Extrude1, Face<7>@Cut-Extrude1, Face<8>@Cut-Extrude1, Face<9>@Cut-Extrude1, Face<10>@Cut-Extrude1, Face<11>@Cut-Extrude1
Coordinate system: Global coordinate system
Reference axis: X

Local Initial Conditions

Initial Condition 1

Thermodynamic Parameters
Static Pressure: 14.695947 lbf/in^2
Pressure potential: On
Temperature: 68.00 °F

Velocity Parameters
Velocity in X direction: 0 ft/s
Velocity in Y direction: 0 ft/s
Velocity in Z direction: 0 ft/s
Turbulence parameters type: Turbulent energy and dissipation
Energy: 0.000430 Btu/lb
Dissipation: 0.33 lbf*ft/s/lb

Concentrations
Substance fraction by volume
Air
Air: Table from X coordinate
Hydrogen Sulfide
Hydrogen Sulfide: Table from X coordinate

Initial Condition 2

Thermodynamic Parameters
Static Pressure: 14.695947 lbf/in^2
Pressure potential: On
Temperature: 68.00 °F
Velocity Parameters
   Velocity in X direction:  0 ft/s
   Velocity in Y direction:  0 ft/s
   Velocity in Z direction:  0 ft/s
Turbulence parameters type:  Turbulent energy and dissipation
   Energy:  0.000430 Btu/lb
   Dissipation:  0.33 lbf*ft/s/lb

Concentrations
   Substance fraction by volume
   Air
   Air:  Table from X coordinate
   Hydrogen Sulfide
   Hydrogen Sulfide:  Table from X coordinate

Perforated Plates
   Perforated Plate 1
      Faces:  Face<1>
      Perforated plates:  Perforated Ceiling 0.5" holes 2" x 6"

Porous Media
   Porous Medium 1
      Porous medium:  2in Corrected Swine Floor Grating
      Coordinate system:  Global coordinate system
      Reference axis:  Y

Goals
Global Goals
   GG Av Static Pressure 1
      Type:  Global Goal
      Goal type:  Static Pressure
      Calculate:  Average value
      Coordinate system:  Global coordinate system
      Criteria:  1.000000 lbf/in^2
      Use in convergence :  On

   GG Av Velocity (X) 1
      Type:  Global Goal
      Goal type:  Velocity (X)
      Calculate:  Average value
      Coordinate system:  Global coordinate system
      Criteria:  1.000 ft/s
      Use in convergence :  On

   GG Av Velocity (Y) 1
      Type:  Global Goal
      Goal type:  Velocity (Y)
      Calculate:  Average value
      Coordinate system:  Global coordinate system
      Criteria:  1.000 ft/s
      Use in convergence :  On

   GG Av Velocity (Z) 1
      Type:  Global Goal
      Goal type:  Velocity (Z)
Calculate: Average value
Coordinate system: Global coordinate system
Criteria: 1.000 ft/s
Use in convergence: On

GG Av Turbulent Energy 1
Type: Global Goal
Goal type: Turbulent Energy
Calculate: Average value
Coordinate system: Global coordinate system
Criteria: 1.000000 Btu/lb
Use in convergence: On

GG Av Turbulent Dissipation 1
Type: Global Goal
Goal type: Turbulent Dissipation
Calculate: Average value
Coordinate system: Global coordinate system
Criteria: 1.00 lbf*ft/s/lb
Use in convergence: On

GG Av Volume Fraction of Hydrogen Sulfide 1
Type: Global Goal
Goal type: Volume Fraction of
Calculate: Average value
Coordinate system: Global coordinate system
Use in convergence: Off

GG Max Volume Fraction of Hydrogen Sulfide 1
Type: Global Goal
Goal type: Volume Fraction of
Calculate: Maximum value
Coordinate system: Global coordinate system
Criteria: 0.1000 ppm
Use in convergence: On

GG Mass (Fluid) 1
Type: Global Goal
Goal type: Mass (Fluid)
Coordinate system: Global coordinate system
Criteria: 1.000 lb
Use in convergence: On

Point Goals

PG Volume Fraction of Hydrogen Sulfide 1 MX6-1
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: MX6-1 -12in
X: 17.198 ft
Y: -0.667 ft
Z: 4.042 ft
Use in convergence: Off

PG Volume Fraction of Hydrogen Sulfide 2 MX6-2
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: MX6-2 -12in
X: -17.198 ft
Y: -0.667 ft
Z: 4.042 ft
Use in convergence :  Off

PG Volume Fraction of Hydrogen Sulfide 3 MX6-3
Type:  Point Goal
Goal type:  Volume Fraction of
Coordinate system:  Global coordinate system
Name:  MX6-3 +24in
X:  17.198 ft
Y:  2.333 ft
Z:  4.042 ft
Use in convergence :  Off

PG Volume Fraction of Hydrogen Sulfide 4 MX6-4
Type:  Point Goal
Goal type:  Volume Fraction of
Coordinate system:  Global coordinate system
Name:  MX6-4 +24in
X:  -17.198 ft
Y:  2.333 ft
Z:  4.042 ft
Use in convergence :  Off

PG Volume Fraction of Hydrogen Sulfide 5 MX6-5
Type:  Point Goal
Goal type:  Volume Fraction of
Coordinate system:  Global coordinate system
Name:  MX6-5 +6in
X:  12.104 ft
Y:  0.833 ft
Z:  4.042 ft
Use in convergence :  Off

PG Volume Fraction of Hydrogen Sulfide 6 MX6-6
Type:  Point Goal
Goal type:  Volume Fraction of
Coordinate system:  Global coordinate system
Name:  MX6-6 +6in
X:  12.104 ft
Y:  0.833 ft
Z:  -2.042 ft
Use in convergence :  Off

PG Volume Fraction of Hydrogen Sulfide 7 MX6-7
Type:  Point Goal
Goal type:  Volume Fraction of
Coordinate system:  Global coordinate system
Name:  MX6-7 +6in
X:  0.104 ft
Y:  0.833 ft
Z:  -1.042 ft
Use in convergence :  Off

PG Volume Fraction of Hydrogen Sulfide 8 MX6-8
Type:  Point Goal
Goal type:  Volume Fraction of
Coordinate system:  Global coordinate system
Name:  MX6-8 +6in
X:  0.104 ft
Y:  0.833 ft
Z:  -2.042 ft
Use in convergence :  Off
PG Volume Fraction of Hydrogen Sulfide 9 MX6-9
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: MX6-9 +6in
X: -11.837 ft
Y: 0.833 ft
Z: 5.042 ft
Use in convergence: Off

PG Volume Fraction of Hydrogen Sulfide 10 MX6-10
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: MX6-10 +6in
X: -11.896 ft
Y: 0.833 ft
Z: -2.042 ft
Use in convergence: Off

PG Volume Fraction of Hydrogen Sulfide 11 MX6-11
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: MX6-11 +6in
X: -14.198 ft
Y: 0.833 ft
Z: 2.042 ft
Use in convergence: Off

PG Volume Fraction of Hydrogen Sulfide 12 TX1-1
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: TX1-1 -12in
X: 6.000 ft
Y: -0.667 ft
Z: -2.182 ft
Use in convergence: Off

PG Volume Fraction of Hydrogen Sulfide 13 TX1-3
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: TX1-3 -12in
X: 0 ft
Y: -0.667 ft
Z: -2.182 ft
Use in convergence: Off

PG Volume Fraction of Hydrogen Sulfide 14 TX1-2
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: TX1-2 -12in
X: -6.000 ft
Y: -0.667 ft
Z: -2.182 ft
Use in convergence: Off

PG Volume Fraction of Hydrogen Sulfide 15 TX1-4
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: TX1-4 -12in
X: -12.000 ft
Y: -0.667 ft
Z: -2.182 ft
Use in convergence: Off

PG Volume Fraction of Hydrogen Sulfide 16 M40-2
Type: Point Goal
Goal type: Volume Fraction of
Coordinate system: Global coordinate system
Name: M40 Window
X: 18.177 ft
Y: 3.333 ft
Z: 2.625 ft
Use in convergence: Off

Calculation Control Options

Finish Conditions
Finish Conditions: If all are satisfied
Maximum physical time: 300.000 s

Solver Refinement
Refinement: Disabled

Results Saving
Save before refinement: On

Periodic Saving
Units: Physical time
Period: 10.000 s

Tabular saving
Units: Physical time
1, 10, 12, 14, 16, 18, 20, 25, 30, 4, 5, 6, 7, 8, 9

Advanced Control Options

Flow Freezing
Flow freezing strategy: Disabled
Manual time step (Freezing): 1.000 s
Manual time step: 1.000 s
Appendix C

Phase II CFD simulation model settings

This section contains the general SolidWorks Flow Simulation 2015 Project Settings used for the Tunnel and Cross-ventilated CFD simulations in Phase II of this research project.

INPUT DATA

Initial Mesh Settings
Automatic initial mesh: Off

Basic Mesh Dimensions
Number of cells in X: 146
Number of cells in Y: 58
Number of cells in Z: 26

Control Planes
Control planes in X direction
<table>
<thead>
<tr>
<th>Name</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Number of cells</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>-50.601</td>
<td>-50.000</td>
<td>1</td>
<td>1.000</td>
</tr>
<tr>
<td>X2</td>
<td>-50.000</td>
<td>0</td>
<td>72</td>
<td>1.000</td>
</tr>
<tr>
<td>X3</td>
<td>0</td>
<td>50.000</td>
<td>72</td>
<td>1.000</td>
</tr>
<tr>
<td>X4</td>
<td>50.000</td>
<td>50.601</td>
<td>1</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Control planes in Y direction
<table>
<thead>
<tr>
<th>Name</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Number of cells</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y1</td>
<td>-20.040</td>
<td>0</td>
<td>29</td>
<td>1.000</td>
</tr>
<tr>
<td>Y2</td>
<td>0</td>
<td>20.040</td>
<td>29</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Control planes in Z direction
<table>
<thead>
<tr>
<th>Name</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Number of cells</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1</td>
<td>-8.018</td>
<td>0.250</td>
<td>12</td>
<td>1.000</td>
</tr>
<tr>
<td>Z2</td>
<td>0.250</td>
<td>10.519</td>
<td>14</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Solid/Fluid Interface
Small solid features refinement level: 0
Curvature refinement level: 0
Curvature refinement criterion: 0.555 rad
Tolerance refinement level: 0
Tolerance refinement criterion: 0.125 ft

Refining cells
Refine fluid cells: Off
Refine partial cells: Off
Refine solid cells: Off
Advanced narrow channel refinement: Off

Local Mesh Settings

Local Initial Mesh 1
Components: Face <1RectangularTank-1@Circular Inlet Lid>
Solid/fluid interface
  Small solid features refinement level: 0
  Curvature refinement level: 0
  Curvature refinement criterion: 0.555 rad
  Tolerance refinement level: 0
  Tolerance refinement criterion: 0.125 ft

Refining cells
  Refine all cells: On
  Level of refining all cells: 2

Narrow channels
  Advanced narrow channel refinement: Off

Computational Domain
Size
  X min: -50.601 ft
  X max: 50.601 ft
  Y min: -20.040 ft
  Y max: 20.040 ft
  Z min: -8.018 ft
  Z max: 10.519 ft

Boundary Conditions
  2D plane flow: None
  At X min: Default
  At X max: Default
  At Y min: Default
  At Y max: Default
  At Z min: Default
  At Z max: Default

Physical Features
  Heat conduction in solids: Off
  Time dependent: On
  Gravitational effects: On
  Rotation: Off
  Flow type: Laminar and turbulent
  High Mach number flow: Off
  Humidity: Off
  Default roughness: 0 microinch

Gravitational Settings
  X component: 0 ft/s^2
  Y component: 0 ft/s^2
  Z component: -32.19 ft/s^2
  Default wall conditions: Adiabatic wall

Initial Conditions

  Thermodynamic parameters
    Static Pressure: 14.695947 lbf/in^2
    Temperature: 68.09 °F

  Velocity parameters
    Velocity vector
    Velocity in X direction: 0 ft/s
    Velocity in Y direction: 0 ft/s
    Velocity in Z direction: 0 ft/s
Concentrations
  Substance fraction by volume
  Air
  1000000.00 ppm
  Hydrogen Sulfide
  0 ppm

Turbulence parameters
  Turbulence intensity and length
  Intensity: 1.00e-006 %
  Length: 1.00e-006 in

Material Settings

Fluids
  Air
  Hydrogen Sulfide

Boundary Conditions

Environment Pressure 1
  Type: Environment Pressure
  Faces: Face<1>@TunnelVentilatedBarn-1
  Coordinate system: Face Coordinate System
  Reference axis: X

Thermodynamic parameters
  Environment pressure: 14.695947 lbf/in^2
  Temperature: 68.09 °F

Concentrations
  Substance fraction by volume
  Air
  1000000.00 ppm
  Hydrogen Sulfide
  0 ppm

Turbulence parameters
  Turbulence intensity and length
  Intensity: 1.00e-006 %
  Length: 1.00e-006 in

Boundary layer parameters
  Boundary layer type: Turbulent

Outlet Velocity 1
  Type: Outlet Velocity
  Faces: Face<2>@TunnelVentilatedBarn-1
  Coordinate system: Face Coordinate System
  Reference axis: X

Flow parameters
  Flow vectors direction: Normal to face
  Velocity normal to face: 13.160 ft/s

Inlet Velocity 1
  Type: Inlet Velocity
  Faces: Face<3>@RectangularTank-1
  Coordinate system: Face Coordinate System
  Reference axis: X
Flow parameters
  Flow vectors direction: Normal to face
  Velocity normal to face: 42.440 ft/s
  Fully developed flow: No

Thermodynamic parameters
  Approximate pressure: 14.695947 lbf/in^2
  Temperature: 68.09 °F

Concentrations
  Substance fraction by volume
  Air: 1000000.00 ppm
  Hydrogen Sulfide: 0 ppm

Turbulence parameters
  Turbulence intensity and length
  Intensity: 5.00 %
  Length: 4.86 in

Boundary layer parameters
  Boundary layer type: Laminar

Local Initial Conditions

Initial Condition 1

Thermodynamic Parameters
  Static Pressure: 14.695947 lbf/in^2
  Pressure potential: On
  Temperature: 68.09 °F

Velocity Parameters
  Velocity in X direction: 0 ft/s
  Velocity in Y direction: 0 ft/s
  Velocity in Z direction: 0 ft/s
  Turbulence parameters type: Turbulence intensity and length
  Intensity: 1.00e-006 %
  Length: 1.00e-006 in

Concentrations
  Substance fraction by volume
  Air: 999900.00 ppm
  Hydrogen Sulfide: 100.00 ppm

Porous Media

Porous Medium 1
  Components: Cover Body#RectangularTank-1@TunnelVentilatedBarnWithRectangularTank
  Porous medium: Slotted Flooring 2in slot 6in slat 3in border
  3ft x 10ft section
  Coordinate system: Global coordinate system
  Reference axis: Z

Goals

Global Goals
GG Av Static Pressure 1
  Type: Global Goal
  Goal type: Static Pressure
  Calculate: Average value
  Coordinate system: Global coordinate system
  Use in convergence: On

GG Av Velocity (X) 1
  Type: Global Goal
  Goal type: Velocity (X)
  Calculate: Average value
  Coordinate system: Global coordinate system
  Use in convergence: On

GG Av Velocity (Y) 1
  Type: Global Goal
  Goal type: Velocity (Y)
  Calculate: Average value
  Coordinate system: Global coordinate system
  Use in convergence: On

GG Av Velocity (Z) 1
  Type: Global Goal
  Goal type: Velocity (Z)
  Calculate: Average value
  Coordinate system: Global coordinate system
  Use in convergence: On

GG Av Turbulent Energy 1
  Type: Global Goal
  Goal type: Turbulent Energy
  Calculate: Average value
  Coordinate system: Global coordinate system
  Use in convergence: On

GG Av Turbulent Dissipation 1
  Type: Global Goal
  Goal type: Turbulent Dissipation
  Calculate: Average value
  Coordinate system: Global coordinate system
  Use in convergence: On

GG Max Volume Fraction of Hydrogen Sulfide 1
  Type: Global Goal
  Goal type: Volume Fraction of
  Calculate: Maximum value
  Coordinate system: Global coordinate system
  Use in convergence: Off

GG Mass (Fluid) 1
  Type: Global Goal
  Goal type: Mass (Fluid)
  Coordinate system: Global coordinate system
  Use in convergence: On

GG Av Volume Fraction of Hydrogen Sulfide 1
  Type: Global Goal
  Goal type: Volume Fraction of
  Calculate: Average value
  Coordinate system: Global coordinate system
  Use in convergence: Off
Surface Goals

SG Pit-safety fan Inlet Mass Flow Rate 1
Type: Surface Goal
Goal type: Mass Flow Rate
Faces: Face<1>@RectangularTank-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Pit-safety fan Inlet Volume Flow Rate 1
Type: Surface Goal
Goal type: Volume Flow Rate
Faces: Face<1>@RectangularTank-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Pit-safety fan Inlet Av Velocity 1
Type: Surface Goal
Goal type: Velocity
Calculate: Average value
Faces: Face<1>@RectangularTank-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Pit-safety fan Inlet Av Velocity (Z) 1
Type: Surface Goal
Goal type: Velocity (Z)
Calculate: Average value
Faces: Face<1>@RectangularTank-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Barn Inlet Mass Flow Rate 1
Type: Surface Goal
Goal type: Mass Flow Rate
Faces: Face<1>@TunnelVentilatedBarn-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Barn Inlet Volume Flow Rate 1
Type: Surface Goal
Goal type: Volume Flow Rate
Faces: Face<1>@TunnelVentilatedBarn-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Barn Inlet Av Velocity 1
Type: Surface Goal
Goal type: Velocity
Calculate: Average value
Faces: Face<1>@TunnelVentilatedBarn-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Barn Inlet Av Velocity (X) 1
Type: Surface Goal
Goal type: Velocity (X)
Calculate: Average value
Faces: Face<1>@TunnelVentilatedBarn-1
Coordinate system: Global coordinate system
Use in convergence: Off
SG Barn Fan Outlet Mass Flow Rate 1
Type: Surface Goal
Goal type: Mass Flow Rate
Faces: Face<1>@TunnelVentilatedBarn-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Barn Fan Outlet Volume Flow Rate 1
Type: Surface Goal
Goal type: Volume Flow Rate
Faces: Face<1>@TunnelVentilatedBarn-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Barn Fan Outlet Av Velocity 1
Type: Surface Goal
Goal type: Velocity
Calculate: Average value
Faces: Face<1>@TunnelVentilatedBarn-1
Coordinate system: Global coordinate system
Use in convergence: Off

SG Barn Fan Outlet Av Velocity (X) 1
Type: Surface Goal
Goal type: Velocity (X)
Calculate: Average value
Faces: Face<1>@TunnelVentilatedBarn-1
Coordinate system: Global coordinate system
Use in convergence: Off

Volume Goals

VG Pit Max Volume Fraction of Hydrogen Sulfide 1
Type: Volume Goal
Goal type: Volume Fraction of
Calculate: Maximum value
Components: Chimney Airspace Combine Right@RectangularTank-1@TunnelVentilatedBarnWithRectangularTank
Coordinate system: Global coordinate system
Use in convergence: On

VG Barn Max Volume Fract of Hydrogen Sulfide 1
Type: Volume Goal
Goal type: Volume Fraction of
Calculate: Maximum value
Components: Barn Internal Airspace@TunnelVentilatedBarn-BarnWithRectangularTank
Coordinate system: Global coordinate system
Use in convergence: Off

Calculation Control Options

Finish Conditions
Finish Conditions: If all are satisfied
Maximum physical time: 300.000 s

Solver Refinement
Refinement: Disabled

Results Saving
Save before refinement: On
Periodic Saving
Units: Physical time
Period: 10.000 s

Tabular saving
Units: Physical time
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 25, 30

Advanced Control Options

Flow Freezing
Flow freezing strategy: Disabled
Manual time step (Freezing): Off
Manual time step: 0.250 s
VITA

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Education

Ph.D. Agricultural and Biological Engineering, 2018
The Pennsylvania State University, University Park, PA

M.S. Agricultural and Biological Engineering, 2011
The Pennsylvania State University, University Park, PA

B.S. Engineering Technology, 1997
University of Delaware, Newark, DE

Employment

Extension Research Assistant, Agricultural and Biological Engineering Department
The Pennsylvania State University, University Park, PA
July 2015 to December 2017

Research Assistant, Agricultural and Biological Engineering Department
The Pennsylvania State University, University Park, PA
January 2012 to May 2015

Instructor, Agricultural and Biological Engineering Department
The Pennsylvania State University, University Park, PA
August 2011 to December 2011

Graduate Assistant, Agricultural and Biological Engineering Department
The Pennsylvania State University, University Park, PA
January 2010 to July 2011

Lead Engineer
Nutrient Control Systems, Inc., Chambersburg, PA
May 2003 to July 2009

Agricultural Machinery Specialist
McLanahan Corporation, Agricultural Machinery Systems Division, Hollidaysburg, PA
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Journal Articles

